

Restoration of Performance and Recovery in Elite Level Rugby Union

Adam Grainger - University of Salford, Salford, UK (00371562)

A THESIS SUBMITTED TO THE SCHOOL OF HEALTH SCIENCES AT
SALFORD UNIVERISTY IN PARTIAL FULFILLMENT OF THE DEGREE OF
DOCTOR OF PHILOSOPHY, FEBRUARY 2017.

Contents

List of tables	vii
List of figures	viii
Acknowledgements	x
Declaration	xi
Abbreviations	xii
Abstract	xv
1 Introduction	1
1.1 Match demands in rugby union	1
1.2 Restoration of performance post rugby match play	1
1.3 The effect of rugby match play upon recovery	2
2 Literature Review	4
2.1 Demands of rugby union	5
2.1.1 Physical characteristics and performance capabilities of a rugby union player.....	9
2.1.1.1 Playing levels and physical characteristics.....	9
2.1.1.2 Positional physical characteristics of an elite level rugby union player	10
2.1.1.2.1 Strength and power of elite rugby union players	11
2.1.1.2.2 Speed capabilities of elite rugby union players	11
2.1.1.2.3 Aerobic and anaerobic ability of elite rugby union players.....	12
2.1.1.2.4 Body mass and composition of elite rugby union players.....	20
2.1.1.3 Which physical elements enhance the likelihood of success of an elite level rugby union player?.....	20
2.1.2 The use of GPS data for optimal performance	21
2.1.3 Training week structure and RPE	22
2.1.4 Summary	23
2.2 Methods of strength and power training and assessment in rugby	24
2.2.1 Resistance training methods	24
2.2.2 Strength and power training specifically	24
2.2.2.1 Effect of strength and power training on subsequent performance.....	25
2.2.3 Implications for practitioners	26
2.2.4 Summary	27
2.3 Performance Tests, Fatigue and Associated Recovery	28
2.3.1 Tests of Performance	28
2.3.2 Fatigue science.....	28
2.3.2.1 Central fatigue	33
2.3.2.2 Peripheral fatigue.....	33
2.3.2.3 Biochemistry of fatigue.....	34
2.3.2.3.1 Depletion and fatigue	34
2.3.2.3.2 Metabolic by-products and fatigue.....	35
2.3.2.3.3 Neural fatigue and the excitation-contraction-relaxation processes	36
2.3.3 Neuromuscular fatigue.....	36
2.3.3.1 Mechanisms of neuromuscular fatigue.....	36

2.3.3.2	Models of fatigue	37
2.3.4	Factors affected by fatigue which are important for performance.....	40
2.3.5	Assessing fatigue.....	40
2.3.6	Fatigue and rugby.....	42
2.3.7	Restoration of Performance.....	46
2.3.8	Recovering from team sport activities	47
2.3.9	What is readiness?	51
2.3.10	Summary.....	52
2.4	Methods of Assessing Fatigue, Recovery and Readiness	53
2.4.1	Maximal and sub-maximal performance tests.....	54
2.4.1.1	Maximal strength testing.....	56
2.4.1.2	Maximal Jump testing.....	58
2.4.1.2.1	Common uses of jump testing.....	58
2.4.1.2.2	Jump testing tools	58
2.4.1.2.3	Jump testing – kinetic and outcome based measures	61
2.4.1.2.4	Jump performance to assess fatigue	62
2.4.1.2.5	The relevance of jump testing in elite performance settings.....	63
2.4.1.3	Maximal ergometer testing.....	65
2.4.2	Running specific performance tests for football codes.....	65
2.4.3	Perceptual feelings of well-being.....	67
2.4.4	Biochemical markers	69
2.4.4.1	Muscle damage and biochemical response.....	70
2.4.4.2	Hormonal response.....	71
2.4.4.3	Metabolic response to rugby game play.....	72
2.4.4.4	Considerations for biochemical testing.....	73
2.4.5	Heart rate derived measures.....	74
2.4.5.1	Resting heart rate.....	74
2.4.5.2	Heart rate variability	74
2.4.5.3	Heart rate recovery	77
2.4.5.4	Considerations for heart rate derived data and responses to exercise.....	79
2.4.6	Summary	79
2.5	Strategies used to Enhance Restoration of Performance and Recovery	80
2.5.1	Commonly used recovery modalities	80
2.5.1.1	Ice baths and contrast water therapy.....	81
2.5.1.2	Whole Body Cryotherapy (WBC).....	82
2.5.1.3	Compression garments	83
2.5.1.4	Active recovery.....	84
2.5.1.5	Sports massage.....	85
2.5.1.6	Sleep to aid recovery.....	86
2.5.1.7	Nutritional interventions to aid recovery.....	87
2.5.1.8	Rest and days without training	89
2.5.1.9	Selecting the appropriate recovery modality	91
2.5.2	Summary	92
2.6	Relevance of readiness and restoration research	93
2.6.1	The importance of readiness	93
2.6.2	Meaningful change	94
2.6.3	Improving readiness	96
2.6.4	Limitations of the research to date	97
2.7	Summary of research proposed.....	98

2.7.1	Research questions proposed	99
3	Match Characteristics in an Elite Rugby Union Playing Season.....	100
3.1	Abstract.....	100
3.2	Introduction	100
3.3	Method.....	104
3.3.1	Experimental Approach.....	104
3.3.2	Match analysis.....	105
3.3.3	Statistical Analyses	106
3.4	Results	106
3.4.1	Match characteristics between forwards and backs	106
3.4.2	Match characteristics between the nine positional groups.....	108
3.5	Discussion	117
3.5.1	Limitations of this study	122
3.6	Practical Applications	124
3.7	Implications of experimental chapter 3 for subsequent studies.....	125
4	Within and Between-Session Reliability of Jump Performance in Elite Rugby Union Players	126
4.1	Abstract.....	126
4.2	Introduction	126
4.3	Materials and methods	129
4.3.1	Participants	129
4.3.2	Jumps	129
4.3.2.1	Countermovement Jump (CMJ) technique	129
4.3.2.2	Squat Jump (SJ) technique.....	129
4.3.2.3	Single Leg Drop Jumps (SLDJ) technique	130
4.3.3	Procedure.....	130
4.3.3.1	Instrument.....	130
4.3.3.2	Jump Height and Flight time.....	131
4.3.4	Statistical Analyses	131
4.4	Results	131
4.4.1	Within-session variability and reliability.....	131
4.4.2	Between-session	134
4.5	Discussion	134
4.5.1	Within-session	134
4.5.2	Between-session	134
4.5.3	Limitations of this study	135
4.6	Practical Applications	135
4.7	Implications of experimental chapter 4 for subsequent studies.....	136
5	Countermovement Jump in Elite Rugby Players – A comparison between devices	137
5.1	Abstract.....	137
5.2	Introduction	137
5.3	Method.....	139
5.3.1	Participants	139
5.3.2	Procedure.....	140
5.3.2.1	Countermovement Jump (CMJ) technique	140

5.3.2.2	Instruments	140
5.3.2.2.1	Force plate.....	140
5.3.2.2.2	OptoJump.....	141
5.3.2.3	Data analysis.....	141
5.3.2.3.1	Jump Height and Flight Time	141
5.3.2.3.2	Force-time analysis	142
5.3.3	Statistical Analyses	142
5.4	Results	143
5.4.1	Jump height measures from <i>OptoJump</i> and force plate	143
5.5	Discussion	145
5.5.1	Jump height measures from <i>OptoJump</i> in comparison to force plate	145
5.5.2	Reliability of <i>OptoJump</i> and force plate.....	147
5.5.3	Jump height in comparison to RFD	149
5.5.4	Limitations of this study	150
5.6	Practical Applications	151
5.7	Implications of experimental chapter 5 for subsequent studies.....	152
6	Between-Session Reliability of a Countermovement Jump in Elite Rugby Players Pre Game	153
6.1	Abstract.....	153
6.2	Introduction	153
6.3	Method.....	154
6.3.1	Participants	154
6.3.2	Procedure.....	155
6.3.2.1	Instrument.....	155
6.3.2.2	Countermovement Jump (CMJ) technique	155
6.3.2.3	Jump Height and Flight Time	155
6.3.3	Statistical Analyses	155
6.4	Results	156
6.4.1	Between-session reliability of a single CMJ per testing day.....	156
6.5	Discussion	156
6.5.1	Limitations of this study	157
6.6	Practical Applications	158
6.7	Implications of experimental chapter 6 for subsequent studies.....	159
7	Change in Countermovement Jump Performance and Well-being Scores of Professional Rugby Union Players Post-match.....	160
7.1	Abstract.....	160
7.2	Introduction	160
7.3	Method.....	163
7.3.1	Participants	163
7.3.2	Experimental Approach.....	163
7.3.3	Jump testing	164
7.3.4	Self-report well-being questionnaires.....	164
7.3.5	Match analysis and GPS data	165
7.3.6	Statistical Analyses	165
7.4	Results	166
7.4.1	Changes in CMJ performance pre to post-match	166

7.4.2	Changes in WB performance post-match.....	167
7.4.3	A comparison of changes in CMJ performance pre and post-match between forwards and backs.....	168
7.4.4	A comparison of changes in WB performance pre and post-match between forwards and backs.....	169
7.4.5	Relationships between match data and changes in CMJ performance and WB scores.....	170
7.4.6	Relationships between match data and changes in CMJ performance and WB scores across positional groups.....	171
7.5	Discussion	171
7.5.1	Normal CMJ change.....	172
7.5.1.1	CMJ performance between positional groups.....	173
7.5.2	Normal WB change	174
7.5.2.1	WB scores between positional groups.....	175
7.5.3	Performance reduction across 170 hours assessing both CMJ and WB	176
7.5.4	Relevance of GPS parameters upon CMJ performance and WB scores.....	176
7.5.4.1	Relevance of GPS parameters upon CMJ performance and WB scores between positional groups	177
7.5.5	Limitations of the research.....	178
7.6	Practical implications	179
7.7	Implications of experimental chapter 7 for subsequent studies.....	180
8	Quantification of GPS impacts using video analysis in Elite Level Rugby Union.....	181
8.1	Abstract.....	181
8.2	Introduction	181
8.3	Method.....	184
8.3.1	Participants	184
8.3.2	Experimental approach.....	185
8.3.3	Match analysis.....	185
8.3.3.1	GPS analysis.....	185
8.3.3.2	Video analysis	186
8.3.4	Statistical analyses	186
8.4	Results	187
8.5	Discussion	190
8.5.1	Impacts resulting from collisions	191
8.5.2	Impacts resulting from changes of direction, accelerations and decelerations	191
8.5.3	Impact categorisation	193
8.5.4	Limitations of the research.....	193
8.5.5	Future research directions	194
8.6	Practical applications.....	195
9	Thesis discussion	197
9.1	Introduction and recap of existing research	197
9.2	Major findings of the research	197
9.3	Limitations of the research conducted.....	200
9.3.1	“Real world” limitations.....	200
9.3.2	Limitations of CMJ protocol implemented.....	201

9.3.3	GPS limitations.....	203
9.4	Practical applications and future research directions as a result of the research conducted	205
9.4.1	Future jump testing protocol to assess restoration of performance	205
9.4.2	Application of subjective and objective measures of restoration	207
9.4.3	Position-specific tests of performance restoration	207
9.4.4	Future GPS integration for recovery intervention	209
9.4.5	Athletic resilience, training loads and hastened restoration of performance.....	211
9.4.6	Physiological and psychological restoration post rugby union match play	213
9.5	Final conclusion	214
10	References	215
11	Appendix	245
11.1	Appendix A	245
11.2	Appendix B	246
11.3	Appendix C.....	247

List of tables

Table 2.1: Player positions and roles within the game adapted from Duthie et al. (2003).....	p5
Table 2.2: Research showing limitations of match distance data in rugby union.....	p6
Table 2.3: Research showing limitations of match intensity data in rugby union.....	p7
Table 2.4: Research showing match sprinting data in rugby union	p7
Table 2.5: Research showing limitations of match heart rate data in rugby union.....	p8
Table 2.6: Research showing assessment of upper body and lower body strength characteristics of different rugby union playing levels.....	p14
Table 2.7: Research showing assessment of upper body and lower body power measurement characteristics of different rugby union playing levels.....	p15
Table 2.8: Research showing assessment of short sprint characteristics of different rugby union playing levels	p16
Table 2.9: Research showing assessment of agility characteristics of different rugby union playing levels.....	p17
Table 2.10: Research showing assessment of aerobic and anaerobic characteristics of different rugby union playing levels	p18
Table 2.11: Research showing physical characteristics of rugby union players	p19
Table 2.12: Exercise fatigue models and the theories associated with them	p39
Table 2.13: An overview of performance measures utilised in rugby	p54
Table 3.1: Physical characteristics of players assessed	p104
Table 3.2: Example training week.....	p105
Table 3.3: Categorisation of distances covered and impacts.....	p106
Table 3.4: Descriptive statistics (mean \pm standard deviations; CI=95% confidence intervals), effects sizes and statistical power, across distance data for forwards and backs.....	p107
Table 3.5: Descriptive statistics (mean \pm standard deviations; CI=95% confidence intervals), effect sizes and statistical power, across impact zones for forwards and backs.....	p107
Table 3.6: Descriptive statistics (mean \pm standard deviations; CI=95% confidence intervals) across selected match demands data for all positions.....	p109
Table 3.7: Descriptive statistics (mean \pm standard deviations; CI=95% confidence intervals) across distance data for all positions (symbols presented on table 20).....	p112
Table 3.8: Key for descriptive distance data in table 3.7	p113

Table 3.9: Descriptive statistics (mean \pm standard deviations; CI=95% confidence intervals) across impacts data for all positions.....	p116
Table 4.1: Descriptive (mean \pm standard deviations) and reliability statistics, within testing days for jump height for CMJ, SJ and SLDJ.....	p131
Table 4.2: Descriptive (mean \pm standard deviations) and reliability statistics, between testing days for CMJ, SJ and SLDJ.....	p134
Table 5.1: Descriptive (mean \pm standard deviations) and reliability statistics, within testing days for CMJ height and RFD ($N.s^{-1}$).....	p143
Table 5.2: Descriptive (mean \pm standard deviations) and reliability statistics, between testing days for CMJ height (cm) and RFD ($N.s^{-1}$).....	p145
Table 7.1: Categorisation of distances covered and impacts.....	p165
Table 7.2: Relationships between match data and changes in CMJ performance and WB scores.....	p170
Table 7.3: Relationships between match data and changes in CMJ performance and WB scores across positional groups.....	p171
Table 8.1: Categorisation of impact zones.....	p186
Table 8.2: Key of significant differences in percentage distribution of impacts across Zones 4, 5 and 6 for each activity relating to Figure 8.3.....	p190

List of figures

Figure 2.1: Schematic of fatigue models.....	p31
Figure 2.2: Schematic of muscle fatigue mechanisms adapted from Abbiss and Laursen (2005).....	p32
Figure 2.3: Training adaptation theory adapted from Bompa and Haff (2009).....	p49
Figure 4.1: Bland-Altman plot for CMJ within session one.....	p132
Figure 4.2: Bland-Altman plot for SJ within session one.....	p132
Figure 4.3: Bland-Altman plot for SLDJL within session one.....	p133
Figure 4.4: Bland-Altman plot for SLDJR within session one.....	p133
Figure 5.1: An illustration of the test set up, showing the <i>OptoJump</i> sitting alongside the force plate.....	p141
Figure 5.2: Relationship between <i>OptoJump</i> jump height (from flight time) and force plate flight time during the same jump, using pooled data.....	p144
Figure 5.3: Relationship between jump height from flight time on a force plate and jump height derived from velocity at take-off on a force plate, using pooled data.....	p144

Figure 5.4: Relationship between jump height from velocity at take-off on a force plate and jump height derived from flight time on an <i>OptoJump</i> , using pooled data.....	p145
Figure 6.1: CMJ height for testing days one and two.....	p156
Figure 7.1: Comparison of CMJ performances pre and post-match (n=59).....	p168
Figure 7.2: Changes in wellbeing scores pre to post-match (n=59).....	p169
Figure 7.3: Changes in CMJ performance pre to post-match (Forwards n=31; Backs n=28)...	p170
Figure 7.4: Changes in WB score pre to post-match (Forwards n=31; Backs n=28).....	p170
Figure 8.1: Frequency of impacts in Zones 4, 5 and 6 for each activity.....	p188
Figure 8.2: Percentage of impacts in Zones 4, 5 and 6 for each activity.....	p189
Figure 8.3: Percentage distribution of impacts across Zones 4, 5 and 6 for each activity.....	p190

Acknowledgements

I am delighted to acknowledge colleagues, friends and family for the support and inspiration I have received over the period of my candidature.

First and foremost, I would like to thank my principal supervisor, Dr Paul Comfort, whose patience and diligence, as well as his practical and academic experience, has been invaluable to me. I also offer my sincere appreciation to my associate supervisor Dr John McMahon, whom I am especially grateful for your assistance during the kinetic comparison sections of this work. Both Paul and John's practical knowledge and love for sports science inspired me throughout this candidacy and pushed me to work outside my comfort zone in the laboratory. Their capacity to reply to emails and provide valuable feedback on many draft versions was invaluable and I sincerely thank you. Additionally, I am extremely grateful for the opportunity to complete my PhD at Salford University, and I would like to acknowledge the support that Sale Sharks Rugby Club played in this process.

I finish by thanking those closest to me. I am forever grateful to my wife for her absolute confidence in me. Thank you for the never-ending support you showed me throughout this long process and for your understanding of the time this took away from the family. From a man who has worked in team sports all his life, I can firmly say you are the best teammate I have ever seen. Additionally, I would like to thank my two children for being so understanding when Daddy was ignoring their requests as he had his head in his work! It is now time for me to give attention back to you! A mention also for my mother in law who has supported me throughout this journey and understood my desire to complete this body of work. Lastly, thank you to my parents who started me on the path to education many years ago and I hope I have made you proud despite the ups and downs along the way.

This research was not supported by any external financial support and the author has no conflict of interest with the products examined.

Declaration

I certify that the thesis I have presented for examination for the PhD degree of Salford University is solely my own work. The copyright of this thesis rests with the author. Quotation from it is permitted, provided that full acknowledgement is made. This thesis may not be reproduced without my prior written consent. I warrant that this authorisation does not, to the best of my belief, infringe the rights of any third party.

Abbreviations

(%1RM) – Percentage One Repetition Maximum
(1RM) - One Repetition Maximum
(acute:chronic) – Acute to chronic training load ratio
(ANS) - Autonomic Nervous System
(ASSQ) - Athlete Sleep Screening Questionnaire
(ATP) - Adenosine Triphosphate
(AU) - Arbitrary Units
(BAM) - The Brief Assessment of Mood questionnaire
(bpm) - Beats per minute
(C) - Cortisol
(CA++) - Calcium Calcification
(CHO) - Carbohydrate
(CI) - Confidence Interval
(CK) - Creatine Kinase
(cm) - centimetres
(CMJ) - Countermovement Jump
(CNS) - Central Nervous System
(CP) - Creatine Phosphate
(CT) - Computerised Tomography
(CV) - Coefficient of Variance
(CWI) - Cold Water Immersion
(CWT) - Contrast Water Treatment
(DJ) - Drop Jump
(DJ-RSI) - Drop Jump Reactive Strength Index
(DOMS) - Delayed Onset of Muscle Soreness
(DSL) - Dynamic Stress Load
(ECC)- Excitation-Contraction Coupling
(ECR) - The Excitation–Contraction–Relaxation Cycle
(EIMD) - Exercise Induced Muscle Damage
(EMG) - Electromyography
(F) - Force
(FOR) - Functional Overreaching
(FT:CT) - Flight time to Contraction Time
(g) - grams
(G) - Gravitation Force
(GAS) - The General Adaptation Theory
(GI) - Glycaemic Index
(GPS) - Global Positioning System
(H+) - Hydrogen Ion
(HF) - High Frequency
(HFF) - High Frequency Fatigue
(HIMS) - Heart Rate Interval Monitoring System
(HR) - Heart Rate
(hr:min) - hours and minutes
(HRex) - Heart Rate Exertion
(HRR) - Heart Rate Recovery
(HRR%) - Heart Rate Recovery percentage
(HRR60s) - Heart Rate Recovery within 60 seconds
(HRV) - Heart Rate Variability
(HSR) – High Speed Running
(Hz) - Hertz
(ICC) - Interclass Correlation Coefficients

(IMTCP) - Isometric Mid Thigh Pull
 (JH) - Jump Height
 (kg/s) - Kilograms per second
 (km) - Kilometres
 (km/h) - Kilometres per hour
 (LFF) - Low Frequency Fatigue
 (L/min) - Litres per minute
 (rMSSD) - Root mean square of successive differences used to assess heart rate variability
 (LNSD1) - Vagal-related heart rate variability index
 (LPM) - Load per minute
 (MAS) - Maximal Aerobic Speed
 (m) - Metres
 (min) - Minute
 (ms) - Milliseconds
 (m.s⁻¹) - Metres per second
 (ml.kg.min⁻¹) - Units of millimetres of oxygen per kilogram of body weight per minute
 (mmol.l) - Millimoles per litre
 (mmol.l⁻¹) - Millimoles per litre per kilogram
 (mmol glucosyl.kg.DM⁻¹) - Muscle glycogen levels per kilogram
 (MP) Metabolic Power
 (mRFD) - Mean rate of force development
 (MRI) - Metabolic Reaction Index
 (MRIS) - Magnetic Resonance Imaging Scan
 (MRS) - Magnetic Resonance Spectroscopy
 (MSFT) - Multi Stage Fatigue Test
 (MVIC) - Maximal Voluntary Contraction
 (N) - Newtons
 (N.s⁻¹) - Newtons per second
 (NFL) - National Football League
 (NFOR) - Non Functional Overreaching
 (NMF) - Neuromuscular Fatigue
 (NREM) - Non Rapid Eye Movement
 (OR) - Overreaching
 (OTS) - Overtraining System
 (PAP) - Post Activation Potentiation
 (PFK) - Phosphofructokinase
 (Pi) - Phosphates
 (pg ml⁻¹) - Picogram per millilitre
 (Pmax) - Maximal power
 (PNN50) - Proportion of number of pairs of successive NN intervals divided by the total
 (POMS) - Profile of Mood States questionnaire
 (PP) - Peak Power
 (PRFD) - Peak Rate of Force Development
 (R-R Interval) - The calculation used to assess the time between any two QRS complexes
 (REM) - Rapid Eye Movement
 (Rest-Q-76Sport) - The Recovery Sport Questionnaire for Athletes consisting of 76 statements
 (Rest-Q-Sport) - The Recovery Sport Questionnaire for Athletes
 (RFD) - Rate of Force Development
 (RHIE) - Repeated High Intensity Efforts
 (RHR) - Resting Heart Rate
 (RLMSP) - Rugby League Match Simulation Protocol
 (RMSSD) - Root Mean Square of the Successive Differences
 (RPE) - Rate of Perceived Exertion
 (RTP) - Return to play

(s) - Seconds
 (SD1) - Short Term Heart Rate Variability
 (SDD) - Smallest Detectable Difference
 (SEM) - Smallest Error of Measurement
 (SFRA) - Stimulus-Fatigue-Recovery-Adaptation Theory
 (SJ) - Squat Jump
 (SLDJ) - Single Leg Drop Jump
 (SM) - System Mass
 (SNDN) – The standard deviation of normal R-R intervals
 (SSC) - Stretch Shortening Cycle
 (SWC) - Smallest Worthwhile Change
 (T) - Testosterone
 (T:C) - Testosterone to Cortisol ratio
 (TL) - Training Load
 (TRIMP) - Training Impulse to monitor Training Load
 (U/L) - Units per Litre
 (v) – Velocity
 (VJD) - Vertical jump displacement
 (VGRF) – Vertical ground reaction force
 ($\dot{V}O_{2max}$) - The maximal rate of oxygen consumption as measured during incremental exercise
 (W) – Watts
 (WADA) - World Anti-Doping Agency
 (WB) - Well-being questionnaire
 (WBC) - Whole Body Cryotherapy
 (w/kg) Watts per kilogram
 (YoYo IE2) - Yo-Yo Intermittent Endurance Test Stage 2
 (YoYo IR1) - Yo-Yo Intermittent Recovery Test Stage 1
 (YoYo IR2) - Yo-Yo Intermittent Recovery Test Stage 2

Abstract

Fatigue in the days post rugby union match play is expected, yet accurate assessment of fatigue needs to be quantified via specific performance testing, to better advise practitioners regarding likely position-specific time-course of recovery. Results from this thesis support the notion that countermovement jump (CMJ) provides sensitive and reliable data for jump performance monitoring in elite rugby union settings, with a change in jump height of $\geq 1.7\%$ noted as meaningful. Additional findings from this thesis support the use of a single CMJ (measuring jump height) using an *OptoJump*, as a reliable measure ($CV < 10\%$) for assessing post-match levels of jump performance when a force plate is not readily available. The analysis of nine positional groups within this thesis added to the current knowledge base of match demands research, with differences identified both between backs and forwards and also within these two positional groups. When assessing time-course of recovery post-match play, CMJ performance was reduced at 60 hours post-match, 90 hours post-match and 170 hours (seven days), yet well-being score was reduced to a greater extent (-9%) and for a longer time-course than CMJ (-6%). Unlike hypothesised, it is recommend that practitioners be advised to consider backs as having a longer time-course of recovery, compared to forwards, with the decrement in performance for up to 7 days post-match within both positional groups having implications for training prescription between matches. Lastly, as hypothesised, collisions accounted for a higher percentage of the higher magnitude impacts than other match demands such as accelerations, decelerations and changes of direction. The differences in activities which account for the impact classification is an important consideration for future global positioning systems (GPS) application in elite rugby union settings when assessing likely fatigue created by match play, with the use of both video analysis alongside GPS data recommended.

1 Introduction

1.1 Match demands in rugby union

Rugby union like with many other team sports is a sport of intermittent activities of both high intensity and low intensity periods, with many gait changes performed during game phases (Austin, Gabbett, & Jenkins, 2011a; Quarrie, Hopkins, Anthony, & Gill, 2013). The ability to identify and understand the specific demands placed upon sports performers during match-play and training situations has long since been recognised as a crucial factor in developing appropriate training and recovery programmes which may elicit improved performance (Coughlan, Green, Pook, Toolan, & O'Connor, 2011; Quarrie et al., 2013; Roberts, Trewartha, Higgitt, El-Abd, & Stokes, 2008). Important aspects for successful performance within rugby union match play include strength, power, speed and both aerobic and anaerobic capacity (Argus, Gill, Keogh, Hopkins, & Beaven, 2010; Cunniffe, Proctor, Baker, & Davies, 2009), with increases in size and strength amongst players noted to correlate with on field performance (Argus et al., 2010).

Increased commercial interest in rugby union since it became professional in 1995 has led to players receiving better analysis and management of training to optimise performance in matches, resulting in the game reported to becoming faster, containing more phases and involving bigger, faster and more physical players (Lombard, Durandt, Masimla, Green, & Lambert, 2015; Quarrie et al., 2013). A typical professional rugby season in the northern hemisphere contains over 30 games (Quarrie et al., 2016), and involves blunt force trauma and high running volumes in training and matches. Recent investigations into the training and match load that players encounter was noted as a concern (Quarrie et al., 2016), with the management of load recognised as an important element in enabling professional players to perform regularly in an optimal state. Distances covered in games have been reported to vary from 5000-7000 m across positional groups (Cahill, Lamb, Worsfold, Headey, & Murray, 2013; Roberts et al., 2008), with backs generally completing more distance than forwards and international players covering a greater distance than club professionals over the same game duration. The distance covered within match situations consist of a range of sprints, changes of direction, jumps and contacts (with both opposition players and the playing surface), therefore creating fatigue and muscle damage.

1.2 Restoration of performance post rugby match play

The intense exercise associated with rugby union match play has been shown to cause temporal impairments in immune function with disturbances in immunity lasting up to 38 hours post-recovery (Cunniffe et al., 2010). Time periods for a reduction in performance post-rugby match have also been reported by West et al. (2014) who noted CMJ [peak power output (PPO)] decreased below baseline at 12 hours (baseline 6100 ± 565 W vs. 12 h 5680 ± 589 W; $p = 0.004$) and 36 hours (5761 ± 639 W; $p < 0.001$), but had recovered at 60 hours (5950 ± 505 W; $p = 0.151$). The volume and intensity of work, including associated trauma from contact situations completed in a rugby union match play can result in illness and injury potential and increased exercise recovery time, meaning post-competition recovery periods are an integral component in the management of the players (Cunniffe et al., 2010). The need to restore performance as soon as possible is of importance within elite rugby union where

games are weekly and often the number of days between games is as low as five within many professional rugby competitions. Players therefore need to restore performance to enable completion of meaningful training between games, which will increase the chance of optimal performance, and success in subsequent games despite the associated fatigue and trauma created by prior match demands.

1.3 The effect of rugby match play upon recovery

A competitive game of rugby union lasts for approximately 90 minutes and involves high intensity activities including moments of blunt force impact and sprinting (Austin et al., 2011a). Data from a recent study in the English Premiership rugby union league, reported match distances averaged across a season as being 5850 ± 1101 m for forwards and 6545 ± 1055 m for backs per game (Cahill et al., 2013), with high intensity bouts and high impact forces being a major source of cumulative fatigue throughout a game. Cunniffe et al. (2009) revealed that the average number of impacts was over 1000 per game. Correlations between the total number of impacts experienced within elite rugby league match play and compromised neuromuscular function assessed via jump performance in the 48 hours post-match have been reported (McLellan & Lovell, 2012). Takarada (2003) concluded that direct impacts of tackles on the body were the major cause of muscle damage, but that repeated intermittent sprinting was also a major contributor. Both the trauma caused from contact and eccentric actions (often experienced during deceleration phases of a change of direction movement) reduces the capacity of the damaged muscle to generate force. McLellan and Lovell (2012) researched fatigue in rugby league and reported that homeostasis only returned 48 hours post-match and that blunt force trauma and energy system depletion should be further investigated to optimise subsequent performance. Within the research by McLellan and Lovell (2012) it is important to note that the assessment of homeostasis concerned rate of force development (RFD) during jumping tasks and that biochemical markers of homeostasis took longer to recover (120 hours). In another rugby league study examining changes in neuromuscular fatigue, perceptual and hormonal measures post-match play (McLean, Coutts, Kelly, McGuigan, & Cormack, 2010) CMJ (flight time and relative power), perception of fatigue and overall well-being were also significantly reduced for up to 48 hours post-match.

Neuromuscular fatigue (NMF) is a recently examined area of recovery and fatigue assessment in rugby union research (Marrier et al., 2016; West et al., 2014). NMF is considered a complex area of performance, involving both acute and chronic aspects, some of which relate to aspects of muscle damage and some which relate to energy systems. Despite NMF being multifaceted and complex in nature, this research will focus upon chronic fatigue that is experienced post-match and not acute fatigue that is more commonly experienced during rugby union games, but dissipates with a period of rest in between match involvements. Many of the other factors involved within fatigue research are examined in more detail within Chapter 2. It is important for practitioners to acknowledge that each fatigue factor detailed below may require a different approach to optimise recovery. A greater understanding of player global fatigue, player well-being and the relationship with readiness to train after match play is key for improved recovery and effective management of subsequent training weeks. The importance of such research is further emphasised when considering that a link exists between subsequent performance and injury risk as a result of sub-optimal recovery post-match in rugby league (Murray, Gabbett, & Chamari, 2014). The assessment of recovery and restoration of performance in the days post-

match via monitoring tools outlined below should enable coaches in elite rugby to make informed decisions upon timing, frequency and intensity of training in the days post-match and is likely to result in optimal recovery, reduced injury risk and improved chance of successful subsequent match performances.

The aim of this thesis was to better understand time-course of recovery post rugby union match play, while also identifying monitoring tools that can enable practitioners to make informed decisions upon future training prescription in the days post-match. Another major objective of this research was to determine if this time-course differs across positional groups. This thesis will add to the knowledge of performance measures that can detect meaningful change in NMF as a result of specific match characteristics in rugby union. Elite rugby union players were assessed via examination of both game data taken from global positioning systems (GPS) and video footage assessing movement requirements and the match load involvement for nine positional groups. This innovative methodology provides the sequences of individual position-specific movement patterns and the resultant affect this may have upon fatigue levels, therefore further enabling more informed decisions to be made in the days post-match play across multiple positional groups.

2 Literature Review

The subsequent literature review covers a broad overview of match demands in rugby union and assesses the physiological attributes elite players require for optimal performance, while considering the specific training methods commonly utilised for preparing rugby players for match play. Research reviewed upon match demands and physiological cost of game play will provide a background against which to compare subsequent time-course of recovery investigations, with specific training methods examined due to their likely influence upon time-course of recovery. Performance tests, fatigue science specifically and methods of assessing fatigue were reviewed to develop an understanding of measuring restoration of performance post rugby union match play, and better guide future investigations assessing time-course of recovery. Lastly, commonly used strategies for enhancing restoration of performance post-exercise are reviewed to provide clarity upon the influence of modern sports science practices upon time-course of recovery and the importance of these methods within elite rugby settings.

2.1 Demands of rugby union

Professional rugby union players require well-developed aerobic and anaerobic fitness for competition (Cunniffe et al., 2009). Rugby union is played in two 40 minute halves (Green, Blake, & Caulfield, 2011) with the ball on average in play for 30 minutes; injury time, conversions, penalty shots or the ball being out of play makes up the remainder of the match time (Green et al., 2011). Each team consists of eight forwards and seven backs (Duthie, Pyne, Marsh, & Hooper, 2006), each having a designated position and role, requiring different force-generating and neuromuscular abilities (Table 2.1). All players to a degree are involved in ball carrying, whilst also competing and maintaining possession of the ball requiring physical attributes such as speed, agility, power and strength (Crewther, Lowe, Weatherby, Gill, & Keogh, 2009; Green et al., 2011).

Table 2.1: Player positions and roles within the game adapted from Duthie et al. (2003)

Positional Group	Player position	Physical attributes	Reasoning
Forwards (1-8)	Front row (1-3)	Strength and power.	Gain ball possession, close opposition contact, limited ball running.
	Second row (4-5)	Tall, large body mass and power.	Jump height during lineouts, close opposition contact.
	Loose forwards (6-8)	Strength power, speed and endurance.	Gain and retain possession.
Backs (9-15)	Half backs (9-10)	Speed, endurance.	Control ball possession and evade opposition.
	Midfield backs (12-13)	Strength speed and power.	High contact incidence with opposition.
	Outside backs (11,14-15)	Speed	Evade opposition, large amounts of chasing, defensive and support work.

Roberts et al. (2008) found players to cover distances of 5408-6190 m on average depending upon their positional role, with backs generally covering the greater distances (consisting of multiple high intensity activities including sprinting, jumping and change of direction at various velocities). These demands (distance, accelerations and change of direction) mean that players need to exhibit good lower limb control during high velocity movements in order to perform effectively and minimise the risk of injury. Forwards perform high-intensity static exertion for longer periods than backs, spending eight minutes in intense scrummaging (each lasting 5-20 s) and five minutes in rucks and mauls; contributing to 15% of total game time; compared to four minutes of high-intensity static exertion by the backs (Docherty, Wenger, & Neary, 1988; Duthie, Pyne, & Hooper, 2003a; Roberts et al., 2008). Recent research by Schoeman, Coetzee, and Schall (2015) assessing differences between playing position and collision rates within professional rugby union, noted significant differences between forwards and backs regarding collision rates ($p \leq 0.05$) therefore emphasising the varying demands of rugby union match play. Similarly, using a rolling average approach Delaney et al. (2016) noted small to moderate increases in relative distance and average accelerations between half backs and loose forwards compared to tight five forwards in international rugby union match play (ES = 0.27-1.00).

During the course of a game, players are required to use a range of energy systems, combining low-intensity activity with bouts of various anaerobic high-intensity movements and power-

based tasks in offensive and defensive phases of play. Rugby union is intermittent in nature containing highly explosive sprints and high intensity running with periods of inactivity, thus recognising the importance for all players to obtain good acceleration and lower-limb explosive power. Mean sprint distances during games were reported by Duthie et al. (2006) to range between 11-20 m. Studies using time-motion analysis found sprinting ($> 6.7 \text{ m.s}^{-1}$) occurred on average 16 ± 15 and 23 ± 19 times for forwards and backs respectively, lasting on average $1.2 \pm 0.2 \text{ s}$ (Roberts et al., 2008), with sprinting being found to contribute 10-15% of total “ball in play” game time (Austin et al., 2011a). High intensity runs are performed 41 ± 16 and 59 ± 28 times for forwards and backs respectively lasting on average 1.3-1.5 s (Roberts et al., 2008). Coughlan et al. (2011) reported that players completed 75% of their match activities at low intensity, with backs entering high intensity zones more frequently, while the forward was exposed to a higher number of impacts and total body load measured via an accelerometer. Tables 2.2, 2.3 and 2.4 summarise research that illustrate the match demands of distance, intensity and sprinting variables in rugby union, with the limitations of each study recognised.

Table 2.2: Research showing limitations of match distance data in rugby union

Metric	Reported data	Limitations of research and additional information
Distances	<ul style="list-style-type: none"> • (Roberts et al., 2008) 5408-6190 m on average • (Cahill et al., 2013) $5850 \pm 1101 \text{ m}$ for forwards and $6545 \pm 1055 \text{ m}$ for backs per game • (Coughlan et al., 2011) average distance of 6715 m • (Quarrie et al., 2013) mean distance covered per match ranged from 5400 to 6300 m • (Cunniffe et al., 2009) 6953 m during play • (Jones, West, Crewther, Cook, & Kilduff, 2015) significant differences between positional groups for total absolute difference covered ($p < 0.05$) (Tight forwards $4757 \pm 885 \text{ m}$; Loose forwards $5244 \pm 866 \text{ m}$; Half backs $5693 \pm 823 \text{ m}$; Inside backs $5907 \pm 709 \text{ m}$; Outside backs $6272 \text{ m} \pm 1065$) • (Reid, Cowman, Green, & Coughlan, 2013) 6369 m for forwards and 6842 m for backs per game 	<ul style="list-style-type: none"> • Data taken from players playing 80 minutes only • Distances covered dependent upon positional role • Roberts et al. (2008) data captured by five distributed video cameras • Cahill et al. (2013) data taken across a season with backs travelling greater ($p < 0.05$) absolute and relative distances than the forwards • Coughlan et al. (2011) GPS sampling frequency of 5 Hz • Cahill et al. (2013) GPS sampling frequency of 5 Hz • Cunniffe et al. (2009) GPS sampling frequency of 1 Hz

Table 2.3: Research showing limitations of match intensity data in rugby union

Metric	Reported data	Limitations of research and additional information
Intensity	<ul style="list-style-type: none"> • (Coughlan et al., 2011) players completed 75% of their match activities at low intensity, with backs entering high intensity zones more frequently, while the forward was exposed to higher number of impact and total body load • (Quarrie et al., 2013) distance at speeds >6 m.s⁻¹ (252 m for forwards and 450 m for backs) • (Roberts et al., 2008) high intensity runs are performed 41 ± 16 and 59 ± 28 times for forwards and backs respectively lasting on average 1.3-1.5 s • (Cunniffe et al., 2009) forward entered the lower speed zone (6-12 km/h on a greater number of occasions than the back (315 vs. 229) but spent less time standing and walking (66.5 vs. 77.8%) • (Jones et al., 2015) significant differences between absolute distances covered walking, striding, high- intensity running, low-speed running and high-speed running ($p < 0.05$) (Tight forwards 0.8 ± 0.6; Loose forwards 1.9 ± 1.2; Half backs 2.7 ± 1.3; Inside backs 4.2 ± 1.7; Outside backs 4.3 ± 1.6) • (Reid et al., 2013) that the loose head prop recorded the highest number of entries in both standing and non-purposeful movement (1040 m) and walking zones (1737 m), with the centre (732 m) and fullback (1230 m) the lowest values in this range (0-1.7 m.s) 	<ul style="list-style-type: none"> • Data taken from players playing 80 minutes only • Coughlan et al. (2011) data collected during an international Rugby Union game, yet involved only two players (one back and one forward) • Coughlan et al. (2011) noted differences in total impacts (838 forwards; backs 573) • Quarrie et al. (2013) Data taken 763 players from video recordings of 90 international matches, with distance covered by players at speeds (in excess of >5 m.s) reported to be higher during international matches than when competing at lower levels of the professional game

Table 2.4: Research showing match sprinting data in rugby union

Metric	Reported data	Limitations of research and additional information
Sprinting	<ul style="list-style-type: none"> • (Duthie et al., 2006) mean sprint distances ranging between 11-20 m during games • (Roberts et al., 2008) sprinting occurred on average 16 ± 15 and 23 ± 19 times for forwards and backs respectively, lasting on average 1.2 ± 0.2 s • (Austin et al., 2011a) sprinting being found to contribute 10-15% of total "ball in play" game time • (Cahill et al., 2013) sprinting (Backs 50 ± 76 m) (Forwards 37 ± 64 m) • (Cunniffe et al., 2009) backs performed a greater number of sprints (>20 km/h) than the forwards (34 vs. 19) • (Jones et al., 2015) inside and outside backs performed a significantly greater number of sprints (20, SD = 7 and 20, SD = 6) compared to loose forwards (10, SD = 6) and half backs (12, SD = 5; $p < 0.05$), while tight forwards completed the least number of sprints compared to all other positional groups (4, SD = 3; $p < 0.05$) 	<ul style="list-style-type: none"> • Data taken from players playing 80 minutes only • Back row forwards covered the greatest distances at sprinting (95% Vmax) speeds, particularly the number 8 position (77 m)

Despite forwards completing the majority of their activities at a low speed intensity, heart rate is still within high intensity ranges, as during periods of low speed intensity forwards could be recovering from high intensity bouts of activity, or involved in static movements such as rucks and mauls, that despite being conducted at low speeds are known to involve high exertion (Duthie et al., 2003a; Roberts et al., 2008). Backs, in contrast, were reported by Quarrie et al. (2013) to move greater distances at speeds > 6 m.s⁻¹ compared to forwards. This greater

distance at speeds > 6 m.s⁻¹ (252 m for forwards and 450 m for backs) was due to backs covering a greater average sprint distance than forwards when conducting their movement demands during games. Recent development in GPS technology has attempted to account for these static exertions, with dynamic stress load (DSL) being one such metric that has been utilised recently (*StatSports*, Northern Ireland), with claims that DSL can account for the aspects of fatigue that are not measured via the accelerometer. DSL is, however, unproven in its reliability and applicability to rugby union settings. In addition, recent research assessing metabolic power as a measure of external load (Highton, Mullen, Norris, Oxendale, & Twist, 2016) has illustrated that this metric underestimates the energy expenditure during intermittent collision based sports and therefore should be used with caution. Due to the complexity of assessing static exertions and the resultant effect they have upon fatigue, this research will only assess the dynamic involvements of match play and impacts classified from GPS. Incorporation of indices developed by software companies, such as the DSL associated with *StatSports*, has not been included within past research. Instead the relationship between dynamic movements and restoration and recovery rates post-match play were assessed.

Due to the difference in movement patterns and activities undertaken by positional groups, the exertion and effect upon heart rates during rugby union match play is expected to differ, yet few studies have been published in this area (as is noted within Table 2.5). This difference in cardiovascular response to match play between positional groups needs further investigation. However, it has been reported that high demands are placed on a player's cardiovascular capacity and is reflected in heart rates averaging 172 beats per minute (bpm) which equates to 80 to 85% VO_{2max} during the course of a match (Cunniffe et al., 2009). Deutsch, Maw, Jenkins, and Reaburn (1998) collected heart rates during competition and concluded that forwards experienced a higher mean level of exertion than backs, with forwards spending 72% within high exertion HR zone. Backs in contrast were reported to spend the majority (37%) of their match exertion in a moderate HR zone.

Table 2.5: Research showing limitations of match heart rate data in rugby union

Metric	Reported data	Limitations of research and additional information
Heart rate exertion	<ul style="list-style-type: none"> Cunniffe et al. (2009) reported that heart rates averaging 172 beats per minute (bpm) and players exerting 80 to 85% VO_{2max} during the course of a game 	<ul style="list-style-type: none"> Cunniffe et al. (2009) only involved two players (one forward and one back) using a 1 Hz GPS unit
	<ul style="list-style-type: none"> Deutsch et al. (1998) reported that forwards spending 72% within high exertion HR zone, with backs in contrast reported to spend the majority (37%) of their match exertion in a moderate HR zone 	<ul style="list-style-type: none"> Deutsch et al. (1998) data taken from elite under 19 players upon twenty four players across six games

The difference in match demands within positional groups appears to be vast, with the nature of repeated high intensity effort (RHIE) efforts being specific to position and the resultant effect this has upon time-course of recovery post-match also differing (Cahill et al., 2013; Quarrie et al., 2013; Smart, Hopkins, Quarrie, & Gill, 2014). When considering the differing movement

patterns and load experienced by elite rugby union players, it is interesting to note that Quarrie et al. (2013) recommend that practitioners provide forwards with more time to recover post-match than backs, given the greater contact loads they sustain and subsequent longer restoration of performance time periods. In recent research by Murray et al. (2014) investigating the effect of different between-match recovery times on the activity profiles and injury rates of national rugby league players, position-specific recovery strategies were recommended. However, in consideration that the research by Murray et al. (2014) is based on rugby league and much of the RHIE research also being from rugby league (Austin, Gabbett, & Jenkins, 2011b; Johnston & Gabbett, 2011), rugby union specific data needs examined.

Despite previous research in elite rugby union, presenting data upon player match demands, prior research has not included match characteristics for players that have played less than the entire game (< 80 minutes). Future data collection assessing match demands needs to focus upon all participants within the match to ascertain a greater understanding of the required demands, regardless of whether they played the entire game or not. It is unrealistic to view a player that has played for 40 minutes as likely to complete half the match demands of a player that has played for 80 minutes. Instead, as is commonly accepted within modern rugby union, players are asked to play for less than 80 minutes and are substituted with a player of the same position, which increases the match demands expected as players know they are not being asked to perform for the duration of the match (Quarrie & Hopkins, 2007). This suggests that match demand assessment should follow this format. Another area of focus for this research is the use of 10 Hz GPS units within match characteristics data, as previous research has collected data at different sampling frequencies (Cahill et al., 2013; Coughlan et al., 2011; Cunniffe et al., 2009). When considering that recent research by Rampinini et al. (2015) shows the improved accuracy of 10 Hz GPS in assessing distance covered and high speed running metrics, it is further emphasised that the use of enhanced sampling frequencies is a future area of focus within match characteristics knowledge. Match characteristics data that encompasses 10 Hz GPS analysis is needed across a variety of playing time durations in northern hemisphere rugby union. This use of a higher sampling frequency along with an analytical approach that aims to develop a greater understanding of positional match demands within elite rugby union will likely identify differences between both forwards and backs and the smaller positional groups outlined in Table 2.1.

2.1.1 Physical characteristics and performance capabilities of a rugby union player

Physical characteristics and performance values for professional rugby players are not well documented, perhaps due to the sensitive nature of the data and the competition for marginal gains that exist between professional teams. The following sections detail the difference in physical characteristics and performance capabilities between playing levels, while also providing data upon which elements distinguish an elite level rugby union player from a non-elite level player.

2.1.1.1 Playing levels and physical characteristics

Physical capabilities of elite rugby players differ from amateur players with the differences in strength and power between playing levels being likely due to maturation, training age and body mass (Argus, Gill, & Keogh, 2012). Both lower body (5-15%) and upper body (3-5%) maximal strength increases were reported between 2004 and 2007 in elite rugby players, with these increases in size and strength noted to correlate with on-field performance (Argus et al.,

2010). Significant differences were also noted between anthropometric and physical performance across playing levels, with players at higher levels generally being taller and heavier and capable of improved performance based on physical performance tests (Argus, Gill, & Keogh, 2012). Research by Lombard et al. (2015) supports the view that under 20 players are smaller than senior players and that age grade players present lower strength and sprint values, despite having developed physically over time as represented in Tables 2.6 and 2.8. Physical performance tests commonly utilised in rugby union are examined in more detail in Chapter 2.3, with the effect of fatigue on performance measures also critiqued in Chapter 2.3.

2.1.1.2 Positional physical characteristics of an elite level rugby union player

Some of the first data published upon physical characteristics of rugby union players in the professional era were presented by Quarrie et al. (1995) who noted significant differences between forwards and backs on anthropometric and physical performance variables. Further research by Quarrie, Handcock, Toomey, and Waller (1996) showed significant positional differences between positional groups, with front row forwards typically being endo-mesomorphic somatotypes, while locks and loose forwards were taller than the front row forwards. It is therefore evident that the physical characteristics of elite level rugby union players are position-specific and ever evolving as the game becomes more professional. More recently, Wood, Coughlan, and Delahunt (2016) presented data from Irish professional rugby union players, showing that forwards (1.85 ± 0.06 m and 96.88 ± 9.00 kg) were significantly ($p < 0.05$) taller and heavier than backs (1.79 ± 0.05 m and 81.97 ± 7.09 kg). The research by Wood et al. (2016) did, however, show that forwards displayed significantly lower ($p < 0.05$) physical performance for a number of tests in comparison to backs (CMJ, Forwards 38.37 ± 4.00 cm, Backs 41.31 ± 4.44 cm; 10 m sprint time Forwards 1.85 ± 0.07 s, Backs 1.77 ± 0.06 s; 150 m shuttle test, Forwards 675.90 ± 82.46 m, Backs 711.71 ± 27.46 m) (Tables 2.6 – 2.11).

Physical performance (speed, power and aerobic ability) differs between forwards and backs, yet fewer positional differences were noted between the smaller positional groups such as props and loose forwards amongst the forwards and halfbacks and outside backs amongst the backs. Much of the physical performance data noted by Quarrie, Handcock, et al. (1996) is detailed in Chapter 2.1.1, yet the sub-elite level of the players within this research makes its worth limited. Duthie et al. (2003a) reported forwards to have superior absolute aerobic and anaerobic power and muscular strength, however, when considering body mass, results favour backs. More recent research by Bell, Evans, Cobner, and Eston (2005) noted that rugby union backs (84.5%) had a significantly lower lean tissue mass than forwards (75.8%), and that forwards (20.6%) had a greater fat mass than backs (11.1%). Game related fatigue has also been noted to differ between forwards and backs in professional rugby, with Tee, Lambert, and Coopoo (2016) noting that forwards experienced progressively greater performance decrements during match play than backs, who were found to maintain performance intensity, despite the match demands encountered.

Positional trends were noted within a ballistic bench throw in semi-professional rugby union players (McMaster, 2015), with forwards producing a greater maximal peak power (PP) during a counter movement bench throw (785 ± 129 W) as well as concentric only bench throw (736 ± 194 W), compared to backs (718 ± 105 W; 683 ± 92 W) respectively. Additional support for differences in maximal strength has been noted by McMaster (2015), with forwards generally demonstrating greater strength level than backs (Table 2.6). Backs are significantly lighter than

forwards (Duthie et al., 2003a) due to their requirement for increased mobility around the field and reduced involvement in scrums and rucks. This reduction in the number of contact situations has led to backs requiring lower maximal strength levels. This is illustrated in Table 2.6, showing reduced one repetition maximum (1RM) performances in all tested measures (Smart, Hopkins, & Gill, 2013) compared to forwards. Smart et al. (2013) noted that loose forwards are the lightest of the forward group with a mean body mass of 101.6 ± 7.9 kg. This reduction in body mass could be the reason behind reduced maximal upper body strength in both bench press and chin ups compared to all other forward positions. As loose forwards have a smaller involvement in scrums, rucks and mauls (Lindsay, Draper, Lewis, Gieseg, & Gill, 2015), the need for this positional bodyweight is therefore emphasised.

Findings in maximum speed research are different from the positional trends in maximal strength, as backs are faster than forwards (Smart et al., 2013) showing that maximal strength is not as important for maximal speed as relative strength is when bodyweight is taken into account (Turner, Tobin, & Delahunt, 2015). Sprint characteristics of rugby union players (Table 2.8) show that forwards are generally slower than backs and from a positional aspect outside backs are the fastest and props are the slowest over all distances. This could be explained by decreased body mass between the positions, with props being the heaviest and backs being the lightest, therefore illustrating that despite bodyweight having an influence upon maximal speed, relative power is a determining factor for speed. Strong correlations between strength and speed have been noted in both rugby union (Cunningham et al., 2013) and rugby league (Kirkpatrick & Comfort, 2013) and are examined in more detail within Chapter 2.1.1.2.2.

2.1.1.2.1 Strength and power of elite rugby union players

Normative strength values for professional players in the premier southern hemisphere rugby competition were noted by Appleby, Newton, and Cormie (2012). When assessing twenty players over a two year period Appleby et al. (2012) noted 1RM for bench press ranging from 132.5 ± 14.0 kg to 146.8 ± 11.5 kg and squat 1RM ranging from 164.6 ± 31.5 kg to 179.1 ± 26.7 kg. Another study of interest for practitioners presenting data from elite rugby union is that by Argus, Gill, Keogh, Hopkins, and Beaven (2009) where 1RM bench press (141 ± 22.5 kg), 1RM box squat (194 ± 32.9 kg) bench throw peak power (1150 W) and jump squat peak power (5190 W) were reported amongst thirty two professional rugby union players from a Super 14 team. Recently reported research assessing strength and power of elite rugby union players is presented in Tables 2.6 and 2.7.

2.1.1.2.2 Speed capabilities of elite rugby union players

In a study assessing neuromuscular performance and relationships with salivary hormones by Crewther et al. (2009), thirty-four professional male rugby players were assessed for running speed, with 10 m (Forwards = 1.85 s Backs = 1.73 s) and 20 m (Forwards = 3.16 s; Backs = 2.96 s) sprint times being significantly different between forwards and backs. Similarly, Quarrie, Handcock, et al. (1996) reported 30 m sprint values for forwards ranging from 3.9-4.1 s, and backs ranging from 3.7-3.28 s. Superior sprinting speed in backs compared to forwards was noted within other research (Duthie et al., 2006), yet the influence of the combination of speed and body mass, leading to greater momentum within forwards is a point for consideration. As noted by Crewther et al. (2009) momentum has a definitive advantage in rugby especially during body contact situations.

Recent research within professional rugby union by Cunningham et al. (2013) highlighted the importance of relative strength and power upon speed components (acceleration and maximum velocity). Relative power in rugby union players is also a determining factor in acceleration, with athletes that have a greater power clean, broad jump and triple broad jump producing quicker 10 m sprint times. This increased power can be explained by their ability to produce force quickly, therefore reducing foot contact time with the ground, as is required for maximal acceleration (Barr, Sheppard, Agar-Newman, & Newton, 2014). The relative peak power during a hexagonal barbell jump squat has also shown a significant relationship between CMJ height and 10 m and 20 m sprint times in professional rugby union athletes playing in the *Pro12* competition (Turner et al., 2015). Perhaps the most interesting recent research assessing speed qualities in international rugby union players was that by Cross, Brughelli, et al. (2015) showing 10 m (Forwards 2.04 ± 0.12 s; Backs 1.95 ± 0.04 s) 20 m (Forwards 3.33 ± 0.15 s; Backs 3.19 ± 0.06 s) and 30 m (Backs 4.32 ± 0.09 s) times, with these values being quicker than international rugby league players within the same study.

Along with straight line speed, rugby is a team sport which requires effective changing of direction (agility) qualities to be a successful rugby union player (Green et al., 2011). Research into change of direction ability of rugby union athletes is well documented (Darrall-Jones, Jones, & Till, 2015; Green et al., 2011; Pienaar & Coetzee, 2013) with studies using a number of different tests with different cutting and change of direction tests implemented (Table 2.9). Similar to rugby union, rugby league players are required to have high levels of agility (Gabbett, Kelly, & Sheppard, 2008). Despite the results being from rugby league, Gabbett et al. (2008) found interesting information for practitioners that shows that there is a small yet not significant ($p > 0.05$, ES = 0.28 to 0.32), difference in change of direction ability between performance levels (higher and lower skilled), with higher skilled players performing change of direction tasks quicker than lower skilled players. Additionally, it is of note that players with faster sprint times over 5, 10 and 20 m were also shown to have a greater change of direction ability (Gabbett et al., 2008). Recently reported research assessing speed of elite rugby union players is presented in Table 2.8.

2.1.1.2.3 Aerobic and anaerobic ability of elite rugby union players

Maximal oxygen uptake (VO_{2max}) has been proposed as an indicator of aerobic fitness in rugby players (Duthie et al., 2003a) with findings that the VO_{2max} of international rugby forwards (51.1 ± 1.4 ml/kg/min) (Warrington, Ryan, Murray, Duffy, & Kirwan, 2001) being lower than players from more running-based sports such as soccer (57.8 ± 6.5 ml/kg/min) and field hockey (61.8 ± 1.8 ml/kg/min) (Duthie et al., 2003a). VO_{2max} values are commonly expressed absolutely as litres per minute (l/min), or when examined in a relative format (where body mass is considered) is compared to body mass per minute (ml/kg/min). Forwards have been noted to have superior absolute VO_{2max} values compared with backs (Jardine, Wiggins, Myburgh, & Noakes, 1988), yet considering that backs typically carry less body mass than forwards, backs relative VO_{2max} values are greater than forwards.

VO_{2max} values are not commonly reported in elite level rugby union, perhaps due to the cumbersome nature of laboratory testing and the limited opportunities that exist to implement such testing within a competitive playing season. Research by Quarrie, Handcock, et al. (1996) on aerobic performance in elite players, has used VO_{2max} testing via a multi-stage shuttle run. Quarrie, Handcock, et al. (1996) reported that backs typically possess greater levels of

endurance fitness than forwards, when assessed via a multi stage shuttle run to predict VO_{2max} . From this research by Quarrie, Handcock, et al. (1996), hookers were noted as having the highest score (58.7 ± 15.2 ml/kg/min), followed by the locks (55.1 ± 15.2 ml/kg/min), loose forwards (55.1 ± 15.2 ml/kg/min) and props (50.8 ± 15.2 ml/kg/min) within the forwards group. For the backs, the inside backs (62.5 ± 16.9 ml/kg/min) produced the highest indication of VO_{2max} , compared with the midfield backs (59.8 ± 16.9 ml/kg/min) and the outside backs (57.6 ± 16.9 ml/kg/min). It is, however, important for practitioners to note that laboratory based testing methodology is perhaps warranted in order to assess precise VO_{2max} values, as the shuttle run test is only a prediction of VO_{2max} rather than a direct measurement. It is therefore apparent that this component is one of several requirements of the overall fitness profile of a rugby player and that anaerobic capabilities are therefore just as important within game demands required for all positions. Considering that rugby players are required to execute tackles, scrummaging and rucking involving accelerations and decelerations during game play, players need the ability to work in intermittent movements that are primarily anaerobic in nature. Recently reported research assessing aerobic and anaerobic qualities of rugby union players is presented in Table 2.10

Table 2.6: Research showing assessment of upper body and lower body strength characteristics of different rugby union playing levels

Author	Subjects	Playing standard	Results
Lombard et al. (2015)	453 subjects who represented the junior national South African National Team between 1998 and 2010	Under 20 internationals	Bench Press increased 40% over a 13 year period (1998, 89 ± 18; 2010, 135 ± 22 kg)
McMaster (2015)	20 subjects (age = 21.2 ± 3.0 years; mass = 94.9)	Semi-professional players	1RM bench press 133.9 ± 9.6 kg for forwards and 110.9 ± 23.9 kg for backs (1.30 kg/BM forwards; 1.24 kg/BM backs)
Darrall-Jones, Jones, and Till (2015)	67 players (under 16s, n = 29; under 18s, n = 23; under 21s, n = 15)	Academy U21 players	1RM bench press for 108.2 ± 14.1 kg (1.11 kg/BM) 1RM front squat for academy U21 players 118.2 ± 17.8 kg (1.24 kg/BM)
Smart et al. (2013)	1161 New Zealand rugby union players from 2004 to 2007	Amateur and professional players	Forwards had small (7.7%; 99% confidence limits ± 8.2% for back squat 1RM) to moderate (13.3%; 64.8% for bench press 1RM)
Cunningham et al. (2013)	20 players (age, 26.5 ± 4.6 years; height, 180.0 ± 10.0 cm; mass, 105.5 ± 11.9 kg)	Professional players	Squat strength 186.2 kg ± 22.6
Appleby et al. (2012)	20 players (12 forwards; 8 backs) with resistance training experience of 10.5 ± 3.3 years	Professional players	1RM bench press ranging from 132.5 ± 14.0 kg to 146.8 ± 11.5 kg and squat 1RM ranging from 164.6 ± 31.5 kg to 179.1 ± 26.7 kg
Argus et al. (2009)	32 players (age, 24.4 ± 2.7 years; height, 184.7 ± 6.2 cm; mass, 104.0 ± 11.2 kg)	Professional players	1RM bench press (141 kg), 1RM box squat (194 kg)
Kilduff et al. (2007)	33 players (13 senior international players) (age, 24.0 ± 3.4 years; height, 185.0 ± 8.0 cm; mass, 97.4 ± 13.4 kg)	Professional players	1RM for bench press of 124 ± 16 kg to 153 ± 23 kg and squat 1RM

Table 2.7: Research showing assessment of upper body and lower body power measurement characteristics of different rugby union playing levels

Author	Subjects	Playing standard	Results
Wood et al. (2016)	89 male players (age, 18.6 ± 0.5 years; height, Forwards 185.0 ± 6.0 cm, Backs 179.0 ± 5.0 cm; mass, Forwards 96.8 ± 9.0 kg, Backs 81.9 ± 7.0 kg)	International under 18 and under 19 players	CMJ height Forwards 38.37 ± 4.00 cm, Backs 41.31 ± 4.44 cm
Tobin and Delahunt (2014)	20 players (age, 22.4 ± 3.4 years; height, 184.0 ± 7.0 cm; mass, 101.2 ± 11.9 kg)	Professional rugby union players	CMJ height to be 43.95 ± 5.43 cm
Cunningham et al. (2013)	20 players (age, 26.5 ± 4.6 years; height, 180.0 ± 10.0 cm; mass, 105.5 ± 11.9 kg)	Professional rugby players	Lower body power CMJ being 5476.1 ± 616.4 W
Argus et al. (2009)	32 players (age, 24.4 ± 2.7 years; height, 184.7 ± 6.2 cm; mass 104.0 ± 11.2 kg)	Professional players	Bench throw peak power (1150 W) and jump squat peak power (5190 W)

Table 2.8: Research showing assessment of short sprint characteristics of different rugby union playing levels

Author	Subjects	Playing standard	Results
Wood et al. (2016)	89 male players (age, 18.6 ± 0.5 years; height, Forwards 185.0 ± 6.0 cm, Backs 179.0 ± 5.0 cm; mass, Forwards 96.8 ± 9.0 kg, Backs 81.9 ± 7.0 kg)	International under 18 and under 19 players	10 m sprint time (Forwards 1.85 ± 0.07 s, Backs 1.77 ± 0.06 s)
Lombard et al., (2015)	453 subjects who represented the junior national South African National Team between 1998 and 2010	Under 20 internationals	10 m sprint times range (1998, 1.86 ± 0.10 ; 2010, 1.73 ± 0.10 s)
Darrall-Jones, Jones, and Till (2015)	67 players (under 16s, n = 29; under 18s, n = 23; under 21s, n = 15)	U21 Academy players	Darrall-Jones, Jones, and Till (2015) within research of U21 Academy players noted 505 left 2.41 ± 0.10 s; 505 right 2.37 ± 0.15 s
Cross, Brughelli, et al. (2015)	15 players (Age; Forwards 28 ± 5 ; Backs 24 ± 3) (Height; Forwards 1.90 ± 0.1 ; Backs 1.82 ± 0.1) (mass; Forwards 114.55 ± 6.3 ; Backs 92.6 ± 4.9)	New Zealand internationals	Cross, Brughelli, et al. (2015) noted 10 m (Forwards 2.04 ± 0.12 s; Backs 1.95 ± 0.04 s) 20 m (Forwards 3.33 ± 0.15 s; Backs 3.19 ± 0.06 s) 30 m (Backs 4.32 ± 0.09 s)
Smart et al. (2013)	1161 New Zealand rugby union players from 2004 to 2007	Both professional and international players	<p>10 m sprint (Props 1.85 ± 4.7 s; Hookers 1.81 ± 4.1 s; Locks 1.79 ± 4.7 s; Loose forwards 1.76 ± 4.5 s; Inside backs 1.72 ± 4.0 s; Centres 1.70 ± 4.0 s; Outside backs 1.68 ± 4.4 s); 20m sprint (Props 3.21 ± 4.4 s; Hookers 3.14 ± 3.7 s; Locks 3.13 ± 4.2 s; Loose forwards 3.06 ± 4.4 s; Inside backs 2.96 ± 3.5 s; Centres 2.95 ± 4.6 s; Outside backs 2.89 ± 3.3 s)</p> <p>Smart et al. (2013) showed backs had small ($1.9 \pm 1.5\%$ for 30 m sprint) to moderate (4.5%; $\pm 1.7\%$ for 20 m sprint) differences in all speed measures between amateur and professional players</p> <p>Small difference in 20 m sprint (1.9%; 62.1% for forwards and 2.2%; 62.2% for backs) between professional and international players</p>
West et al. (2013)	20 players (age, 25.1 ± 3.2 years; height, 185.0 ± 7.0 cm; mass, 90.9 ± 10.6 kg)	Professional rugby union players	10 m sprint time 1.74 ± 0.07 s and 30 m sprint time 4.19 ± 0.19 s in professional rugby union players

Table 2.9: Research showing assessment of agility characteristics of different rugby union playing levels

Author	Subjects	Playing standard	Results
Green et al. (2011)	23 players (Starters age, 21.0 ± 1.65 years; height, 181.0 ± 5.9 cm; mass, 88.9 ± 11.3 kg) (Non starters age, 18.1 ± 1.22 years; height, 176.8 ± 5.4 cm; mass, 81.2 ± 10.1 kg)	Semi-professional players	Green et al. (2011) semi-professional players noted anticipated 45° cut 2.09 ± 0.11 s; unanticipated 45° cut 2.35 ± 0.22 s
Pienaar and Coetzee (2013)	40 players (age, 18.9 ± 0.4 years)	Collegiate players	Pienaar and Coetzee (2013) noted T-Test values of 10.28 ± 0.57 s within collegiate players

Table 2.10: Research showing assessment of aerobic and anaerobic characteristics of different rugby union playing levels

Author	Subjects	Playing standard	Results
Wood et al. (2016)	89 male players (age, 18.6 ± 0.5 years; height, Forwards 185.0 ± 6.0 cm, Backs 179.0 ± 5.0 cm; mass, Forwards 96.8 ± 9.0 kg, Backs 81.9 ± 7.0 kg)	International under 18 and under 19 players	150 m shuttle test, Forwards 675.90 ± 82.46 m, Backs 711.71 ± 27.46 m)
Lombard et al., (2015)	453 subjects who represented the junior national South African national team between 1998 and 2010	Under 20 internationals	Backs assessed via multistage shuttle run test (1998, 101 ± 13 ; 2010, 102 ± 12 shuttles)
Sparks and Coetzee (2013)	21 players (weight 97.6 ± 12.9 kg, height 182.3 ± 7.1 cm, age 22.2 ± 1.2 years)	University rugby union players	Blood lactate of 42.7 ± 6.8 mmol.l during incremental $\dot{V}O_{2\max}$ test to the point of exhaustion in university rugby union players
O'Gorman, Hunter, McDonnacha, and Kirwan (2000)	7 players (weight 93.8 ± 3.7 kg, height 187.0 ± 2.2 cm, age 22.3 ± 0.3 years)	International level rugby players	Blood lactate levels of 18.8 ± 0.3 determined from indirect calorimetry using an incremental protocol
Deutsch et al. (1998)	24 players (weight 88.7 ± 9.9 kg, height 185.0 ± 7.0 cm, age 18.4 ± 0.5 years)	Elite under-19 rugby union players	Mean blood lactate concentration did not differ significantly between groups (range: 4.67 mmol.l for outside backs to 7.22 mmol.l for back row forwards; $p < 0.05$) during competitive matches
Quarrie, Handcock, et al. (1996)	94 players (Props; weight 102.8 kg, height 182.0 cm, age 25.0 years) (Hookers; weight 89.7 kg, height 178.8 cm, age 23.0 years) (Locks; weight 101.9 kg, height 191.8 cm, age 22.4 years) (Loose forwards; weight 96.3 kg, height 186.3 cm, age 21.1 years) (Inside backs; weight 75.0 kg, height 172.7 cm, age 21.7 years) (Midfield backs; weight 85.9 kg, height 179.7 cm, age 21.4 years) (Outside backs; weight 83.4 kg, height 179.4 cm, age 22.5 years)	Senior "A" male rugby players	Anaerobic capacity (six repeated high intensity shuttles) over 70 m showing forwards ranging from 54.3 to 67.4 s, and backs ranging from 39.8-57.8 s on a fatigue index measurement

Table 2.11: Research showing physical characteristics of rugby union players

Author	Subjects	Physical characteristics (Height and weight)	Additional information
Quarrie et al. (1995) Quarrie, Handcock, et al. (1996)	94 senior level rugby players (Age - Forwards 22.7; Backs 21.9)	Height - Forwards 186.0 cm; Backs 177.8 cm; Mass - Forwards 98.5 kg; Backs 81.8 kg	Positional categories within the forwards differed significantly with respect to height, body mass, mesomorphy and ectomorphy, while positional categories of the backs differed significantly in terms of height, body mass, and performance on the aerobic shuttle test.
Duthie et al. (2003a)	A meta-analysis reporting much of the studies above. Forwards are typically heavier, taller, and have a greater proportion of body fat than backs. Training should focus on repeated brief high-intensity efforts with short rest intervals to condition players to the demands of the game. Training for the forwards should emphasize the higher work rates of the game, while extended rest periods can be provided to the backs.		
Bell et al. (2005)	Data taken from 30 young adult Rugby Union players not professional players (15 forwards and 15 backs)	Forwards exhibited larger absolute (kg) of fat mass and lean soft tissue mass than backs	Backs had a significantly larger lean soft tissue mass (%) than forwards at the arms (84.4 vs. 76.5%), legs (80.0 vs. 71.9%) and trunk (89.2 vs. 79.0%), whereas forwards had a greater fat mass (%) than backs at the arms (18.7 vs. 10.6%), legs (23.1 vs. 14.7%), and trunk (18.4 vs. 8.0%)
Quarrie and Hopkins (2007)	Age - Forwards 22.7; Backs 21.9 Player sample size unspecified and data taken from Bledisloe Cup matches between 1972 and 2004	Height - Forwards 190.1 cm; Backs 182.9 cm; Mass - Forwards 111.1 kg; Backs 95.7 kg	Marked differences in match participation times and player size with the introduction of professionalism associated with large increases in passes, tackles, rucks, tries, ball-in- play time, and body mass. Modifications to laws and the application of existing laws has had an impact upon match characteristics.
Argus et al. (2010)	33 elite rugby union players from a Super 14 professional rugby team [Age 24.8 ± 2.4 (All positions)]	Height - 186.1 ± 0.06 cm (All positions); Mass - 102.3 ± 10.3 kg (All positions)	Data taken from a short-term pre-season training programme assessing the effectiveness of a training programme on the body composition and anaerobic performance
Zemski, Slater, and Broad (2015)	37 international Australian rugby players	Height - Forwards 191.0 cm (187.7 to 194.3 cm); Backs 182.6 cm (180.0 to 185.3 cm); Mass - Forwards 111.7 kg (108.1 to 115.2 kg); Backs 91.7 kg (89.1 to 94.3 kg)	Significant differences were also seen between Caucasian and Polynesian forwards in leg lean mass (31.4 kg vs. 35.9 kg, p = 0.014, d = 2.4) and periphery lean mass (43.8 kg vs. 49.6 kg, p = 0.022, d = 2.4)
(Wood et al., 2016)	89 male International under 18 and under 19 players (age, 18.6 ± 0.5 years)	(Height - Forwards 185.0 ± 6.0 cm, Backs 179.0 ± 5.0 cm; Mass - Forwards 96.8 ± 9.0 kg, Backs 81.9 ± 7.0 kg)	Forwards (1.85 ± 0.06 m and 96.88 ± 9.00 kg) (Backs 1.79 ± 0.05 m and 81.97 ± 7.09 kg)

2.1.1.2.4 Body mass and composition of elite rugby union players

In a study assessing rugby union players' physical characteristics in the southern hemisphere, players were reported to have become heavier and backs reported to be taller between the period 1972 and 2004 (Quarrie & Hopkins, 2007). The advent of professionalism in 1995 and the associated advances in training led to an increase in passes, tackles, rucks and ball in play duration. Mean participation time by players is also considered a large determinant of the increased physical size of players, whereby players are often not required to complete the duration of a game and are therefore conditioned accordingly, including an increased body mass. Law changes such as the introduction of the lineout gap in 1972, the increase of points awarded for a try in 1992, the application of increased number of reserves permitted to be allowed on the field in 1997 and the introduction of yellow cards in 2002, have also added to the increased speed of the game and subsequent modified physical characteristics of a modern day rugby union player (Quarrie & Hopkins, 2007). Quarrie and Hopkins (2007) noted that the rapid increase of body mass can be attributed to pressure exerted upon players to compete at an increased size that suited the revised laws of the game. The entitlement to play for less than the whole match duration, due to substitutions, meant that relative aerobic requirements of players were reduced in favour of increased anaerobic ability, to match the amended physical characteristics of a rugby union player in early 2000's. The increasing size of players is illustrated in Table 2.11 and can also be attributed to greater focus and knowledge of resistance training and nutritional interventions that help add lean body mass to players' physiques. This increased stature of rugby union players is perhaps most notable in backs where their physiques are now closely matched to loose forwards of the mid' 1990's, in the hope of helping backs within their increased role of ruck and tackle involvements in the modern game of the late 2000's (Noakes & Du Plessis, 1996). Data from the aforementioned research by Appleby et al. (2012) showed sum of skinfolds ranging from 71.1 ± 16.9 mm to 65.7 ± 16.1 mm across twenty players between 2007 and 2009, with body mass ranging from 103.8 ± 7.6 kg to 106.0 ± 8.4 kg.

2.1.1.3 Which physical elements enhance the likelihood of success of an elite level rugby union player?

As reported in Chapter 2.1.1, the physical elements that distinguish an elite player from a sub-elite player are apparent. The elements that distinguish a successful rugby union player from an unsuccessful rugby player are however less clear. A rugby union player that has the ability to produce elite level attributes will add to the teams' chances of success in games. Other field sports such as football, rugby league and Australian rules football have presented data upon which player characteristics relate to game success, thus providing practitioners with "gold standard" values to compare their playing roster against. Recent research by Smart et al. (2014) assessing the relationship between physical fitness and game behaviours in rugby union players showed that sprint times over 10, 20 and 30 m had moderate to small negative correlations with line breaks ($r = -0.26$), metres advanced ($r = 0.22$), tackle breaks ($r = 0.16$) and tries scored ($r = 0.15$). Smart et al. (2014) also showed that the average time of twelve repeated sprints and percentage body fat in the forwards, along with repeated sprint fatigue in the backs had moderate to small correlations with a measure of activity rate on and around the ball ($r = -0.38$, $r = -0.17$ and $r = -0.17$, respectively).

Considering the previous reported data that physical capabilities of elite rugby players differ from amateur players, with the differences in strength and power between levels of playing being likely due to maturation, training age and body mass (Argus, Gill, & Keogh, 2012), the role of body composition within successful performance is emphasised. Recent research in rugby union by Speranza, Gabbett, Johnston, and Sheppard (2015) demonstrated that the enhancement of lower body muscular strength and power contributed towards improvements in tackling ability, further showing the influence of physical capabilities upon match performance. Speranza et al. (2015) noted a correlation between improvements in 3RM squat and tackling ability ($p = 0.04$; $ES \geq 0.85$) and a small non-significant difference in tackling ability and lower body power ($p = 0.20$; $ES \geq 0.56$) in the responders and non-responders from the research group in question. Similarly, in a longitudinal retrospective assessment of junior players Fontana, Colosio, Da Lozzo, and Pogliaghi (2016) noted that a lower percentage body fat and higher sprint speed over 15 m were the most important predictors of likely career success. In respect of successful match activities, recent research in rugby union (Tierney, Tobin, Blake, & Delahunt, 2016) assessed the running demands of successful and unsuccessful teams, and reported that when forwards achieved greater high speed running (HSR) intensity during attacking 22 entries an increased likelihood of success occurred. The differences in player intensities seen in the study by Tierney et al. (2016), showing successful attacking 22 entries (3.6 m/min^{-1}), compared to unsuccessful attacking 22 entries, illustrate the physical demands required for success, and therefore supports the view that players with higher performance measures (speed, strength, power, repeated sprint ability and body composition) are able to perform to a higher level in game situations.

2.1.2 The use of GPS data for optimal performance

The development of GPS technology is providing sports science practitioners with detailed data relating to specific movement demands of players, while also optimising sport specific training. A critical appraisal of GPS monitoring in team sports was conducted by Cummins, Orr, O'Connor, and West (2013) with six studies detailed across varying playing levels in rugby union, confirming the physical demands placed upon players and the specific metrics involved. GPS data is collected throughout rugby players' training weeks (microcycles) and longitudinally over an entire playing season with many studies published recently on game data (Austin et al., 2011a; Cahill et al., 2013; Coughlan et al., 2011; Quarrie et al., 2013). Despite GPS not being a testing tool regularly used in the field for assessing NMF or readiness, GPS does help guide practitioners upon the volume of training undertaken, which can be invaluable information for readiness assessment, when combined with many of the monitoring tools discussed below (Chapter 2.4). The need to analyse GPS data and the associated training volume (distances, speeds and dynamic stress load for example) has been utilised in a number of rugby union studies (Austin et al., 2011a; Cahill et al., 2013; Coughlan et al., 2011) and is considered to be an essential tool of many elite sport team practitioners, giving detailed information on both external load (i.e. distance) and internal load (i.e. HR), thus providing a more global assessment of exercise intensity.

Limitations of GPS technology exist, as represented in a review of GPS reliability (Buchheit et al., 2014) showing substantial differences between different models, with variations ranging from 1% variation in maximal speed assessments and 56% difference on decelerations between GPS models. These large variations therefore question the usefulness of acceleration and deceleration measures, with Buchheit et al. (2014) strongly advising practitioners to apply care

when comparing data collected with different models. Similarly, research collected by Coutts and Duffield (2010) advised that different devices should not be used interchangeably, yet an acceptable level of accuracy and reliability was noted for total distance and peak speeds in team sport settings. This same research, however, did find poor reliability for higher intensity activities (high intensity running > 14.4 km/h) and noted better accuracy over linear movements than non-linear movements. It seems, from the data presented by Coutts and Duffield (2010), that GPS devices are more reliable at measuring movements over a low speed and a linear form, compared to rapid accelerations across multiple planes that may be difficult for the GPS device to distinguish between. It is, however, important to note that the technological advances in GPS technology have been vast since the research by Coutts and Duffield (2010), meaning that discrepancies between high intensity activities and non-linear movements are likely to have been resolved, with further evidence supporting the assessment of maximum velocity using 10 Hz GPS units (Roe et al., 2016). The sampling frequencies of the studies in question are detailed in Table 2.2 and may explain some of the variation in data collected. Recent research (Scott, Scott, & Kelly, 2016) assessing the importance of sampling frequency for improving GPS accuracy, noted that 1 Hz and 5 Hz GPS units were not as practical for use in team sports, compared to 10 Hz and 15 Hz units for team sport simulated running movements.

2.1.3 Training week structure and RPE

As reported by Twist and Highton (2013) games in rugby league are supported by periodised training weeks, which are manipulated depending upon the number of days between games. Practitioners have used many methods to evaluate training load (TL) using both internal and external measurements (Killen, Gabbett, & Jenkins, 2010; Lovell, Sirotic, Impellizzeri, & Coutts, 2013). Often the most frequently used form of evaluating internal training load of team sport athletes is calculated via heart rate (Coutts, Rampinini, Marcora, Castagna, & Impellizzeri, 2009; Elloumi, Maso, Michaux, Robert, & Lac, 2003), yet the most commonly used practice within team sports that assess external load utilises rate of perceived exertion (RPE) on a scale measuring from one to ten (Foster et al., 1995) and has been used in many studies (Comyns & Flanagan, 2013; Impellizzeri, Rampinini, Coutts, Sassi, & Marcora, 2004; Lovell et al., 2013; Wallace, Coutts, Bell, Simpson, & Slaterry, 2008), with the intensity score multiplied by the duration of the training session, providing a single number representing the magnitude of that training session. Monitoring training load using numbers calculated to represent training volume can be compared against other performance parameters in order to gauge the effect of the training week and perhaps explain changes in performance (Halson, 2014). As illustrated in recent research by Thornton et al. (2015) in elite rugby league, the effectiveness of self-report data when utilising TL and WB data for predicting illness is evident (weekly-TL > 2786; WB < 7.25). Practitioners can use training load data to examine load-performance relationships and plan future training load prescription, thus reducing the risk of injury illness and NFOR.

Previous research in both team sports (Coutts et al., 2009; Impellizzeri et al., 2004; Lovell et al., 2013) and individual sports (Rodríguez-Marroyo, Villa, Garcí'A-Lopez, & Foster, 2012) has presented strong correlations between HR and session RPE. Lovell et al. (2013) also reported large correlations between session RPE and GPS derived measures of distance and high speed running. In contrast, body load measurements taken from GPS have shown contrasting correlations to session RPE, with Gomez-Piriz, Jimenez-Reyes, and Ruiz-Ruiz (2011) showing low correlating values in soccer while Lovell et al. (2013) showed high correlations. As would

be expected on training weeks in team sport settings where days between games are reduced, lower training loads have been prescribed in rugby union and the session RPE method utilised (Elloumi, Maso, Michaux, et al., 2003). On weeks with five days between games, compared to weeks that have more days between games (Killen et al., 2010; McLean et al., 2010; McLellan, Lovell, & Gass, 2011b; Twist, Waldron, Highton, Burt, & Daniels, 2012), lower weekly training load is to be expected. Typically, a training week between games entails two resistance sessions focusing upon strength and power, and three field sessions with focus upon rugby skills and game plans. Inappropriate training loads have been shown to have a negative impact upon player readiness (McLean et al., 2010). Results from McLean et al. (2010) showed that placement and scale of load within each training microcycle between games is important for recovery, and that it is possible to recover both neuromuscular and perceptual measures within four days after a rugby league match. Additionally, it is important to consider all training load measures when assessing the intensity and subsequent physical and mental cost of a training session or game upon an individual. For example, in rugby, many training sessions involve a high wrestling and contact element and are therefore physically difficult to undertake, yet may not display high HR exertion values or metres per minute as seen in “on feet” rugby or conditioning sessions. Recent research illustrating poor management of the days between games in team sports was presented by Malone et al. (2015), where only the day before a game presented consistent periodised training load. This poor management of training load is a major concern for practitioners and one that will result in sub-optimal performance and therefore warrants further investigation in rugby union.

2.1.4 Summary

From the research above it is clear that match demands differ across playing levels and positional groups, with the intermittent nature of rugby union meaning low-intensity activity is mixed with bouts of anaerobic high-intensity movements and power-based tasks during match play. Given the greater contact loads experienced by elite rugby union forwards sustained during match play the load during match play compared to backs, prior research (Cahill et al., 2013; Quarrie et al., 2013; Smart et al., 2014) recommended practitioners provide forwards with more time to recover post-match than backs. Investigations assessing match demands using the most recent advancements in GPS technology and video footage would provide a greater understanding to the physiological cost expected from match play and the resultant response this has upon positional groups in the immediate days post-match. As seen in many elite settings the use of GPS, session RPE and individual training prescription aids in managing the training weeks of team sports players and enables the likelihood of optimal performance between games, via more objective training prescription.

2.2 Methods of strength and power training and assessment in rugby

2.2.1 Resistance training methods

Both field based rugby-specific training and gym based resistance training completed in the days between matches is likely to have an influence upon player fatigue. One of the most commonly used modern rugby resistance training methods include contrast and complex-training (Argus, Gill, Keogh, McGuigan, & Hopkins, 2012; Comyns, Harrison, Hennessy, & Jensen, 2007), with lifts prescribed at a percentage of the maximal possible for one repetition (1RM) and the load-velocity relationship considered accurate for load prescription (Jidovtseff, Harris, Crielaard, & Cronin, 2011). Contrast and complex-training are similar methods of resistance training, with compound training involving heavy resistance days alternated with lighter resistance days and complex-training involving sets of heavy resistance exercise immediately followed by sets of lighter resistance exercise. Despite evidence to support enhanced performance as a result of either complex or contrast-training within rugby union competition phases being limited; a vast body of evidence exists surrounding the effectiveness of strength training (Argus et al., 2010; Baker, 1998, 2001b), with their influence upon acute fatigue also differing (Bevan, Owen, Cunningham, Kingsley, & Kilduff, 2009).

Many practitioners use contrast or complex-training as it is considered a time efficient method for training large groups of team sport athletes within busy training days, where the main focus of the day may be the on field sport specific session and not the resistance training session. Considering the research by Baker (2001b) has shown that levels of strength are often increased or maintained throughout a competition period of a season, yet in-season maximal power was reported within the same study to decrease, the need for a mix of resistance methods is further emphasised. In addition, Appleby et al. (2012) confirmed previous views that as a players training age increases, diminishing return in strength become apparent, meaning a mixed focus to resistance training is again recommended. A mixed focus approach is sometimes known as a mixed method and involves a variety of exercises with loads of 30-70% 1RM to develop power, and loads of 75% and greater used for absolute strength development (Haff & Nimphius, 2012). Despite reported success of mixed methods approach (Cormie, McGuigan, & Newton, 2010b; Schmidbleicher, 1992); difficulty exists for practitioners to determine the best approach for developing maximal strength and power in team sport settings. Mixed methods approach is, however, often used within team sport settings to ensure development of both rate of force development and power output, which are physical elements of movement and explosiveness needed for sports such as rugby union (Haff, Whitley, & Potteiger, 2001). Scientific support for the use of combined training methods on relations among force, velocity, and power development is noted by Toji, Suei, and Kaneko (1997) with further support from Haff and Nimphius (2012, p. 7) in a review of training principles of power noting that “the use of a mixed methods approach to optimize power-generating capacity allows for a superior increase in maximal power output and a greater transfer of training effect because of a more well-rounded development of the force-velocity relationship”.

2.2.2 Strength and power training specifically

The reported increased strength and power of rugby players developed over the past fifteen years has increased attacking and defensive capabilities, increasing the team’s chances of winning and improving the game for audiences (Argus et al., 2010). This increased need for

developing strength and power in rugby players has resulted in time being devoted to strength and conditioning training with specific attention applied to resistance training. Varying resistance training modalities such as isokinetic, isometric and plyometric exist and have been utilised within rugby (Beaven, Cook, & Gill, 2008; Harris, Cronin, Hopkins, & Hansen, 2008; Kilduff et al., 2007; Tobin & Delahunt, 2014) with concurrent training often prescribed due to scheduling constraints for optimal adaptation in the many physical aspects rugby players are required to perform. Evidence supporting the relevance of power movements upon game performance was presented by Hori et al. (2008), who noted a correlation between hang power clean performance and jumping ($r = 0.41$, $p < 0.05$) and 20 m sprint time ($r = -0.058$, $p < 0.01$). When considering the research above by Argus, Gill, Keogh, and Hopkins (2011) and the influence of power upon performance noted by Hori et al. (2008), it is clear that a rugby players ability to produce high power outputs is dependent upon the individuals overall strength and power output.

Recent research (Cormie, McGuigan, & Newton, 2010a; Cormie et al., 2010b; Haff & Stone, 2015) supported the notion of developing high levels of strength before targeting power developing activities, when attempting to improve power outputs generated and warned against the implementation of ballistic strength training alone as decreases in muscular strength have been reported. Instead research by McMaster, Gill, Cronin, and McGuigan (2013) recommended the use of two heavy loaded strength training (75-85% 1RM) sessions per week to counteract declines in strength for rugby players in-season. Within rugby union the ability to produce high levels of power are paramount for successful performance, with a high level of maximal strength being the prerequisite to produce these powerful actions (Argus, Gill, & Keogh, 2012). Despite improvements in power as a result of strength training being well documented (Argus et al., 2011; Baker, 2001a; Cormie et al., 2010a), the relevance of strength training for additional physical adaptations are questioned (Cormie et al., 2010b). The findings by Baker (2001b), however, emphasise the need for more focus on power solely, rather than complex or contrast-training, when assessing elite rugby players. It is, however, important to note that the research by Baker (2001b) incorporated subjects from both professional and amateur settings and is therefore limited in relevance to elite rugby union.

2.2.2.1 Effect of strength and power training on subsequent performance

Unlike other sports, rugby players are required to train in the days between weekly games and do not typically have an extended period of rest post-match to prepare tactically for the next opposition and to create athletic developments prior to the next game. Instead, in the days between rugby union games, elite players typically perform one or two gym-based sessions per week with the aim of maintaining athletic ability and addressing individual anatomical issues in order to maintain their availability for selection. These gym sessions can create both fatigued skeletal muscle and muscle that can be considered potentiated, with the resultant current performance ability of the muscle depending upon the balance between these two factors. The focus, volume and intensity of these gym based sessions is therefore a careful consideration for rugby strength and conditioning practitioners in elite settings, where the aim is to try and improve athletic ability of the players throughout their playing career, while working within the constraints of a nine-month playing season where games appear on a weekly basis.

All forms of resistance training are likely to create NMF if the loads moved and the volumes prescribed are large enough to initiate adaptation. It could, however, be argued that power

training (typically 2-5 reps) would not create as much NMF as strength or hypertrophy training, which, as noted above, involves movements comprising higher loads (%1RM) and more overall volume. Instead, power training involves high intensity movements, which due to the load prescribed often creates less fatigue than strength or hypertrophy focused gym sessions. Strength sessions which contain heavily loaded (%1RM) squat movements are likely to create more eccentric muscle damage than power focused squat movements, thereby having a greater influence upon subsequent performance in the immediate hours and days following this gym session. There is, therefore, a careful balance needed when practitioners prescribe appropriate training modalities (strength, power or hypertrophy) in the days between games.

Improvements in both strength and power abilities of rugby players as a result of a pre-determined training program are common (Harrison & Bourke, 2009). The benefits of resistance training for speed development in male rugby players were reported by Harrison and Bourke (2009), who noted significant decreases ($p = 0.02$) in 5 m and 30 m sprint times for a group that had performed resistance training, in comparison to a group that had not. Further evidence for the benefits of strength training exist from research in rugby union players with Comyns et al. (2007), recommending the implementation of heavy lifting to encourage fast stretch shortening cycle activity and therefore subsequently improve performance. Most significantly perhaps is the research by Argus, Gill, Keogh, et al. (2012) who noted the importance of in-season training upon subsequent performance in rugby union players, whereby recommendations were made for players to perform higher volume contrast-training in comparison to the use of power training alone during competition phases. Results by Argus, Gill, Keogh, et al. (2012) indicate that CMJ performance was improved to a greater level as a result of the strength-power program (50kg CMJ $11.7\% \pm 6.5$) compared to the speed power program (50kg CMJ $3.1\% \pm 4.8$). This further emphasises the importance of concurrent training during competition phases of playing sessions with the potential effect it could have upon subsequent performance.

It is, however, important for practitioners to consider that, as previously mentioned, evidence by Argus et al. (2009) noted that more than two resistance training sessions per week were needed in order to initiate change in elite level rugby union players. Additionally, research of interest is that by Harris et al. (2008) who noted that combination training (strength and power development) increased back squat (11.6%) and decreased 30m sprint time (1.4%) in comparison to that of strength or power training alone. However, the ability for practitioners to implement more than two resistance-training sessions per week is difficult during competition phases in elite rugby union settings, where players are asked to perform many field and gym based sessions per week. Combination-training alongside the other elements of strength development are therefore recommended, yet the importance of incorporating strength elements into these sessions is key, considering the evidence outlined by McMaster et al. (2013). This evidence, therefore, further emphasises the need for implementation of gym based sessions in-season in order to attempt to maintain athletic ability. Additionally, it emphasises the need to choose appropriate exercise selection and session focus within gym sessions, considering the limited windows of opportunity that exist.

2.2.3 Implications for practitioners

From the research above, that reports increased player size and physical capabilities of players, it is evident that the game of rugby union has developed greatly due to the advent of professionalism. As discussed above, advances in training practices (both on the training field

and in the gym) have resulted in increases in strength and power, leading to enhanced or improved match performance. Differing volumes and intensities of training prescribed in the days between matches will result in varying time-course of recovery, with this having major implications for practitioners' training selection in the days post match. Additionally, when considering the anthropometric and physical performance differences noted between positional groups and playing levels (Bell et al., 2005; Quarrie, Feehan, et al., 1996; Quarrie, Handcock, et al., 1996; Quarrie et al., 1995; Quarrie & Hopkins, 2007), the need to select appropriate training methods when considering the goals of each individual within a playing squad is key.

2.2.4 Summary

From the evidence above it is clear that strength and power training is commonly used within rugby to enhance rugby performance, yet contrasting results are presented surrounding the effectiveness of strength training modalities. Despite conflicting evidence for the most beneficial methods of performance enhancement within rugby union existing, the ability to produce high levels of power is paramount for successful performance, with a high level of maximal strength being the prerequisite to produce these powerful actions and therefore recommended for implementation. Practitioners, however, need to be sure that they are providing the correct focus of training and appropriate training dose in the days between games, to enable continued athletic performance maintenance, without adding fatigue and subsequently slowing restoration of performance post-match.

2.3 Performance Tests, Fatigue and Associated Recovery

2.3.1 Tests of Performance

Methods of measuring performance are vast in quantity and in applicability to the sport setting in question, with measures of neuromuscular function, hormonal markers, heart rate derived measures and sub-maximal testing all being utilised. Monitoring of specific performance measures and the associated weekly training volume common within team sport scenarios is a recent area of research. Research that has used modern tools such as: GPS; player monitoring [well-being questionnaires (WB)]; biochemical markers [creatine kinase (CK), cortisol (C), testosterone (T)]; and performance tests (ergometer and jumps), that can all report accurate data, help to aid scientific support for correctly diagnosing performance (McLellan et al., 2011b; Waldron, Twist, Highton, Worsfold, & Daniels, 2011). Other measures of neuromuscular function (performance) include: varying forms of running tests; plyometric push-ups; sprint performances; and isokinetic dynamometry (Duffield, Murphy, Snape, Minett, & Skein, 2012; Johnston et al., 2013; Twist & Sykes, 2011). The most common maximal performance measures used in past research within team sports are maximal strength assessments (Argus et al., 2009; Beaven, Cook, et al., 2008; Comyns, Harrison, & Hennessy, 2010; Harris et al., 2008). In addition, modern practices have included heart rate derived measures to aid practitioners attempting to quantify load and assess performance (Bosquet, Merkari, Arvisais, & Aubert, 2008). Many of the above-mentioned performance tests are used to assess fatigue within elite sport settings, where long seasons and multiple training sessions often present players in fatigued states. A fatigued state is noted as “exhaustion or loss of strength and/or endurance following a strenuous activity” (Medical Dictionary Online, 2015). Methods of assessing fatigue and restoration are examined in more detail in Chapter 2.4, with their relevance to performance and specific tests commonly utilised critiqued.

2.3.2 Fatigue science

One negative consequence of physical activity is fatigue, with exercise-induced fatigue assessed by measuring a decrease in muscle force-generating capacity. Fatigue is commonly known as any reduction in physical or mental performance (Knicker, Renshaw, Oldham, & Cairns, 2011) with the mechanisms for fatigue being task specific and its origin spanning from the cerebral cortex to muscle cross bridge cycling, as is displayed in figure 2.2. Sensations of fatigue are markedly different depending upon the length and intensity of the exhaustive exercise being conducted. The most commonly reported causes of fatigue include: energy system depletion; the accumulation of metabolites; nervous system control; and the failure of the muscle fibres contractile mechanism (Costill, Gollnick, Jansson, Saltin, & Stein, 1973). The causes of fatigue and their relationship to elite rugby are examined in more detail below, yet an important consideration for practitioners is that none of these causes and sites of fatigue can explain all aspects of fatigue created.

Current literature is lacking in its knowledge of the physiological, biochemical and psychological factors that determine fatigue post-physical exertion. As reported by Abbiss and Laursen (2005), when discussing models of fatigue, sports scientists from varying fields will view fatigue in a way that best suits their individual disciplines. A psychologist, for example, may view fatigue as a mental tiredness sensation, while a physiologist may view fatigue as the failure of a specific physiological system to perform at its usual level. Physiological models created to understand exercise fatigue are common, yet their relevance has been critiqued by Noakes

(2000) who, when assessing adaptation and enhancement of athletic performance, questioned why models are unable to explain voluntary exercise termination. As critiqued in Chapter 2.3.2, the majority of research into fatigue during exercise has focused upon the ability of the cardiovascular system to provide enough blood, nutrients and oxygen to the working muscles, or the ability of the energy systems to re-phosphorylate ATP inside the muscle (Noakes, 2000). Post-exercise the fatigue experienced by athletes can be neural, mechanical and metabolic in nature and is not simply being tired; it is a combination of factors that include bodily processes such as the nervous system, the autonomic system, hormonal system, and the muscles themselves. Recent research (Abbiss & Laursen, 2005) has discussed models that explain fatigue, with the proposed non-linear models such as the Cardiovascular/Anaerobic model, Energy Supply/Energy Depletion Model and the Neuromuscular Fatigue Model being detailed in Chapter 2.3.3.2 and in Figures 1.1 and 2.1. Despite significant research into exercise fatigue models, contrasting views exist and are represented in reviews assessing well documented fatigue models (Abbiss & Laursen, 2005; Noakes, 2000) and more recently assessing exercise regulation and the influence of central control (Noakes, 2012; Noakes, Peltonen, & Rusko, 2001). As discussed in more detail below, Noakes et al. (2001) suggested that central skeletal muscle activation is controlled along the neuromuscular pathway in order to protect vital organs from injury and damage.

Most importantly, when assessing models of fatigue, practitioners must understand the differences between acute fatigue (hydrogen ion accumulation or glycogen depletion) (Jardine et al., 1988) compared to chronic fatigue, which may still include substrate depletion but is more likely to relate to muscle damage (Alaphilippe et al., 2012). Both chronic and acute fatigue are the focus of this research, with acute fatigue being more associated with restoration of performance on a short term basis during games (Lacome, Piscione, Hager, & Carling, 2015) (as represented by reduced running performance within rugby union match play) and chronic fatigue symbolising reduced readiness of a rugby player to perform to their optimal potential over a longitudinal period (Alaphilippe et al., 2012). Symptoms of acute fatigue include, firstly, physical factors such as an accumulation of waste products due to muscle contractions (Deutsch et al., 1998; Docherty et al., 1988); and, secondly, mental stress or boredom (Noakes, 2012). Acute fatigue typically recovers following a short period of rest (days) and energy source restoration. Recent research with elite snowboard athletes (Gathercole, Stellingwerff, & Sporer, 2015) illustrates CMJ as a suitable tool for monitoring both acute fatigue and training adaptation. In contrast, symptoms of chronic fatigue include general fatigue that is disproportionate to the intensity of the effort undertaken (Shephard, 2001). Chronic fatigue has been reported to last for up to six months, with a negative energy balance being the resultant effect. In an athletic population chronic fatigue is common, but difficult to diagnose. The acute fatigue resulting from a single training session is expected, yet can accumulate over a longer period to time to create chronic fatigue. This though is normal during periods of high-volume training. Practitioners, however, need to be able to differentiate between this physiological fatigue and more prolonged severe fatigue, which may be due to a pathological condition. This clinical approach was researched by Derman et al. (1997).

Common forms of assessing fatigue include electromyography (EMG) and observations of contractile function with electrical (nerve) and magnetic stimulation (cortex), where the environment within which the athlete is experiencing fatigue plays a role in the depletion of energy sources or accumulation of metabolites (Rahnama, Reilly, Lees, & Graham-Smith, 2003).

Many of the first studies assessing fatigue were laboratory based which, as reported by Gandevia (2001), included attempts by Mosso (1904, cited in Gandevia, 2001) to compare fatigue in voluntary and electrically induced contractions. Further technical advances in fatigue research were implemented by Merton (1954, cited in Gandevia, 2001), where development of superimposed twitch interpolation was key in advancing knowledge in the area. Using an ectograph, Mosso (1904, cited in Gandevia 2001) assessed the distance moved by the middle finger when lifting a 3 kg weight every two seconds before and after instruction. Similar research by Reid (1928, cited in Gandevia, 2001) compared maximal voluntary contraction of finger flexion and force produced by stimulation of the median nerve at the elbow under isometric conditions, with Reid (1928, cited in Gandevia, 2001) concluding that large weights could be lifted by artificial electrical stimulation and not volition, therefore questioning the role of fatigue in termination of exertion tasks. Evidence for the involvement that fatigue has upon maximal efforts during team sport match play was noted by Nagahara, Morin, and Koido (2016), who showed high speed running (as is common in many team sports periods of play) induced impairment of the maximal velocity capabilities of players (as measured via speed tests before and after each half) as a soccer game progresses. This research, therefore, supports the view that fatigue accumulates over the period of match play and that this response has an effect upon the maximal effort tasks required during team sport play.

Despite the aforementioned limitations of laboratory based fatigue research, fatigue assessment via simulated exercise is one area of recent focus within team sport research. Due to the difficulty of investigating muscle activity throughout team sport match play, laboratory based protocols, with surface EMG used to compare electromyographic activity during simulated match events (Rahnama, Lees, & Reilly, 2006; Thorlund, Michalsik, Madsen, & Aagaard, 2008). As was noted in Chapter 2, rugby union match demands involve movements at varying intensities and across multiple planes meaning that a variety of muscle activities and associated fatigue responses are created. Recent research in rugby union by Morel, Rouffet, Bishop, Rota, and Hautier (2015) has shown that EMG level decreases after simulated scrums and mauls (respectively $20.8 \pm 3.2 \%$ and $12.6 \pm 2.5 \%$; $p < 0.0001$), concluding that a greater level of fatigue was evident when compared to sprints and that a larger metabolic activity (Blood lactate accumulation) also existed (Scrums= $7.8 \pm 0.6 \text{ mmol.L}^{-1}$; Mauls= $7.2 \pm 0.6 \text{ mmol.L}^{-1}$; $p = 0.0086$; Sprints $7.1 \pm 0.5 \text{ mmol.L}^{-1}$; $p = 0.001$). Other research in team settings was presented by Thorlund et al. (2008) whereby quadriceps and hamstring maximal voluntary contraction (28%, $p < 0.05$) and peak rate of force development (-30%, $p < 0.05$) were affected concurrently, with marked reductions in muscle EMG following simulated handball match play. It is, however, important for practitioners to note that limitations exist surrounding the fatigue created during a simulated situation (e.g. stimulation of isolated muscles) or laboratory exercise models, and do not relate directly to what happens in sport competition, as noted by Knicker et al. (2011).

Although laboratory based methods are precise and controllable, such monitoring is not feasible in the “real world” team sport environment, which is why assessment of isometric force production via modern technology (dynamometers) and jump performance (force plate and optical measurement) have been used more recently in elite settings. Additionally, it is important to consider that isolated muscle examination via EMG does not assess performance as a whole and only describes the state of that specific muscle, therefore not presenting information upon the athlete’s ability to perform a task, and whether this change in ability to

perform a task has an effect upon subsequent game performance. Recent research assessing monitoring tools to understand fatigue has used both external load quantifying and monitoring tools (such as power output measuring devices, time-motion analysis) and internal load unit measures (including perception of effort, heart rate, blood lactate, and training impulse) (Hals0n, 2014). Methods for assessing fatigue are examined in more detail in Chapter 2.4, with isometric force production and jump performance examined in more detail in Chapters 2.4.1.1 and 2.4.1.2 respectively.

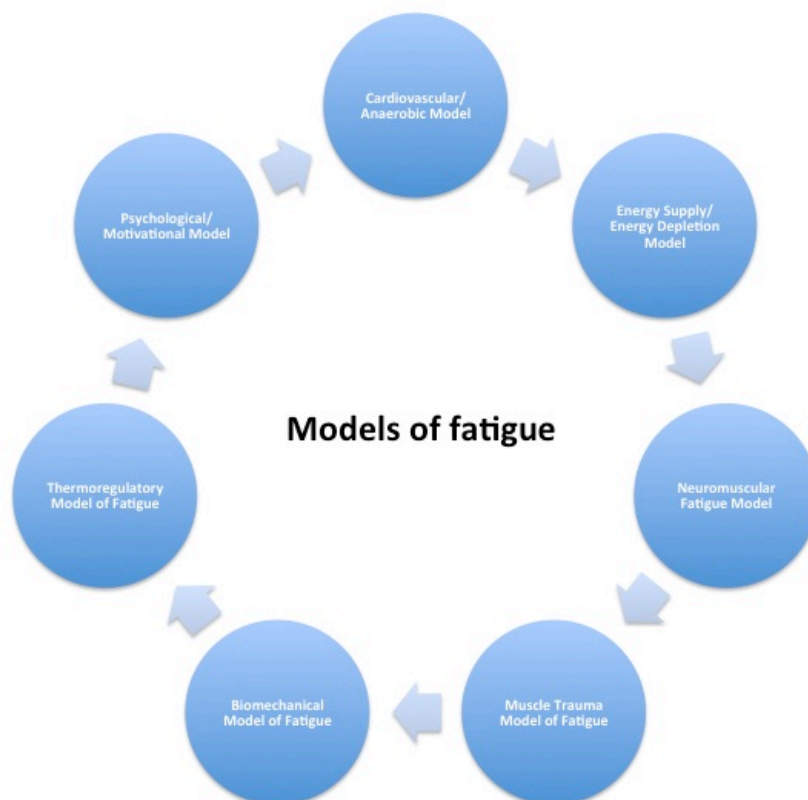


Figure 2.1: Schematic of fatigue models

Fatigue experienced during exercise is reversible with rest (both short and long term recovery), with athletes able to maintain lower intensity exercise despite experiencing fatigue. Identifying the site of fatigue is a complex process, yet one that can provide practitioners with a large amount of detail on the specific condition of individual athletes. As previously mentioned, common sites of fatigue include glycogen depletion and environmental factors that alter an athlete's physiology, such as heat and humidity (Costill et al., 1973). Environmental issues, such as these, affect individual hydration levels thereby contributing to a disturbance of homeostasis. Fatigue during exercise was noted to be influenced by a complex interaction between two commonly reported themes of fatigue; peripheral and central, with a recent study in semi-professional soccer (Thomas, Dent, Howatson, & Goodall, 2017) noting that while central processes contributed towards the fatigue experienced in the days post-match, peripheral fatigue was the primary contributor towards the neuromuscular fatigue experienced. Central

and peripheral fatigue is examined in more detail below in Chapters 2.3.2.1 and 2.3.2.2 and presented in Figure 2.1.

Much of the fatigue research to date within team sports has incorporated the assessment of muscular fatigue, presented as a result of matches, with evidence from soccer being common (Greig, 2008; Rahnama et al., 2003; Thomas et al., 2017), and research from rugby not so prevalent (Duffield et al., 2012; Ronglan, Raastad, & Borgesen, 2006). The fatigue produced within a team sport setting has commonly been assessed by comparing the force of maximal voluntary contraction before and after exercise (Duffield et al., 2012; Ronglan et al., 2006). The original model of fatigue by Hill (1914) proposed that performance during exercise of high intensity was limited by skeletal muscle anaerobiosis, resulting in lactic acid accumulation. However, the proposed theory of Hill (1914) has been critiqued and developed and has led to the “catastrophe theory” (Edwards, 1983), which proposed that “exercise terminates when the physiological and biochemical limits of the body are exceeded, causing a catastrophic failure of intracellular homeostasis” (Noakes and Gibson, 2004, p. 648). More recent criticism of “catastrophe” models of fatigue has been noted, with little published evidence supporting this theory that fatigue occurs only after physiological homeostasis fails. Instead an anticipatory response coordinated in the subconscious brain is considered to be a major contributor to fatigue (Noakes & Gibson, 2004; Noakes, Gibson, & Lambert, 2005). A recent area of focus in fatigue research includes the serotonin hypothesis theory by Meeusen, Watson, Hasegawa, Roelands, and Piacentini (2006). This suggests that an increase in ratio of serotonin to dopamine accelerates the onset of fatigue, whereas a low ratio favours improved performance through the maintenance of motivation and arousal.

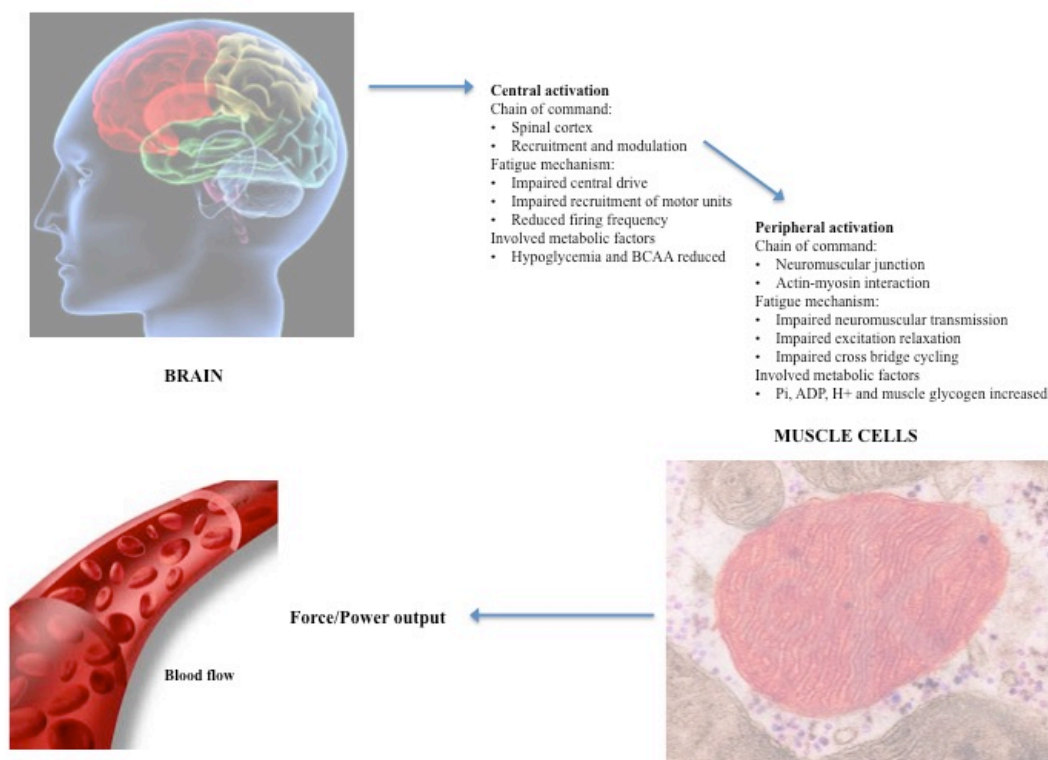


Figure 2.2: Schematic of muscle fatigue mechanisms adapted from Abbiss and Laursen (2005)

2.3.2.1 Central fatigue

Central fatigue is a progressive reduction in voluntary activation of muscle during exercise, resulting in neural inhibition, meaning that greater voluntary effort is required to drive any motor unit. Central fatigue has been known to manifest itself in several ways including central nervous system fatigue, motivation and other psychological factors. Inability to continue exercise experienced by both recreational and elite athletes often occurs despite fatigue being present within the muscles themselves, with pain from central fatigue affecting central drive to continue. However, restoration of force as a result of external stimulation of muscle fibres indicates a central fatigue response, as the muscle is able to continue activity despite fatigue being present. Reduced motor unit firing rate has been reported during central fatigue, suggesting lowered central drive, yet conflicting evidence of “muscle wisdom” has been reported by Garland and Gossen (2002), where improvement in performance under severe fatigue has been noted.

Psychological fatigue is also a consideration for practitioners assessing fatigue during sporting activities, as athletes have been known to learn to minimise the influence of sensory efforts, thus enabling them to approach performance limits within their selected sport. If an athlete reports as fatigued, it is most likely that this fatigue experienced is from some sensory manifestation of the neural regulatory mechanisms, rather than being a consequence of a physiological issue. A notion of the influence of inhibitory control and an ability to resist mental fatigue was noted within a recent study in professional cycling (Rattray, Argus, Martin, Northey, & Driller, 2015), as measured via Stroop test and a time trial on a cycle ergometer. The effect of psychology within central fatigue was further emphasised by the Stechnov phenomenon, which showed faster recovery of strength measures when implementing distraction or “active pause” strategies during recovery from exhaustive tasks. Within the research by Stechnov work output appeared to be significantly greater after an active pause implemented between exercise bouts, rather than after a passive pause.

2.3.2.2 Peripheral fatigue

Potential physiological outcomes of fatigue include reduced muscle force, reduced muscle velocity and power, a need for prolonged relaxation time after fatigue and increased EMG as the muscle looks to recruit more motor units (Kent-Braun, 1999). These mechanisms are considered to be peripheral fatigue, which, in contrast to central fatigue, concerns the peripheral nervous system, with factors affecting peripheral fatigue including: alterations within the excitation-contraction coupling (ECC) process; energy supply changes; and reduction in force generating capacity. Evidence for peripheral fatigue includes that by Petrofsky and Lind (1980) showing large increases in EMG signal with no increase in force present. Petrofsky and Lind (1980) investigated EMG signal in a rectus femoris muscle during graded cycle exercise. This research illustrates that, at higher work rates, the EMG signal increased disproportionately as fatigue developed, with the motor units of the rectus femoris recruiting additional muscle fibres as the work output of fatiguing muscles declined. Additional evidence for peripheral fatigue was noted by Kent-Braun, Miller, and Weiner (1993) when assessing the metabolic phases that occur during progressive exercise to fatigue. Kent-Braun et al. (1993) used a 4 s MVC followed by a 6 s relaxation of the tibialis anterior muscle, in eight healthy humans to demonstrate that three distinct phases of metabolism occur during progressive exercise, all related to the peripheral fatigue response created. The phases included a highly oxidative phase; an intermediate phase; and a highly glycolytic phase, where, as noted by Kent-Braun et

al. (1993) fatigue becomes noteworthy during these phases.

Two theories exist to explain peripheral fatigue; firstly, depletion of energy substrates and secondly, accumulation of metabolic by products (Abbiss & Laursen, 2005; Kent-Braun, 1999). Depletion of energy substrates involves the exhaustion of biochemical products such as adenosine triphosphate (ATP), creatine phosphate (CP) and glycogen. The most common form of metabolic depletion is phosphagen depletion, whereby ATP and CP deplete rapidly, with CP depletion resulting in task failure during high intensity exercise and ATP depletion preserved as fatigue develops. Due to the rapid decrease of CP, it is now common for CP supplementation within many elite sport settings, with metabolic depletion discussed further in Chapter 2.5.1.7. Glycogen depletion, as represented by carbohydrate (CHO) within muscle, is another area of interest for practitioners, especially within prolonged submaximal sport settings that last longer than one hour (Noakes, 2002). Within team sport settings like rugby union, intermittent activities are performed throughout game play at varying exercise intensities (VO_{2max}), meaning that glycogen depletion may occur more quickly than during sub-maximal settings such as marathon running.

Due to glycogen depletion, an athlete's ability to generate ATP is impaired, with task failure common at moderate intensity activities. CHO and the effect of glycogen depletion and potential supplementation used to delay the fatigue response are discussed in more detail in Chapter 2.5.1.7. Accumulation of metabolic by products includes hydrogen ion (H^+), calcium calcification (Ca^{++}) and phosphates (P_i), where the fatigue created is likely to be a combination of the biochemical products, along with the specific conditions of the activity performed. P_i intracellular accumulation involves ATP developing into ADP, during which, when the cell buffering capacity is eventually exceeded, acidosis develops. As noted by Robergs, Ghiasvand, and Parker (2004), in a review of the biochemistry of exercise-induced metabolic acidosis, lactate production is considered to be a consequence rather than a cause of the cellular conditions that cause acidosis. When lactate production is greater than lactate clearance, accumulation develops and where, similarly to P_i accumulation, inhibition of phosphofructokinase (PFK), decreased force production and nausea are perhaps the most commonly seen responses.

2.3.2.3 Biochemistry of fatigue

2.3.2.3.1 Depletion and fatigue

Perhaps the most researched area examining causes of fatigue is that of energy systems (Kent-Braun et al., 1993; Nicholas, Tsintzas, Boobis, & Williams, 1999), although the evidence for energy system fatigue within rugby union specifically is lacking. Muscle glycogen depletion is the most important substrate for energy production in team sport settings (Nedelec et al., 2012) and is a major area of focus for practitioners (Ortenblad, Westerblad, & Nielsen, 2013). Breakdown of muscle glycogen is commonly reported towards the end of soccer games (Krustrup et al., 2006; Mohr, Krustrup, & Bangsbo, 2003), which involve both aerobic and anaerobic exercise. Muscle glycogen depletion, assessed over a three game period, was noted by Krustrup et al. (2006), whereby muscle fibres (mean \pm SEM $73 \pm 6\%$) which were full prior to a soccer game, were recorded as being lower ($p < 0.05$) in glycogen post-match (mean \pm SEM $19 \pm 4\%$). It is also of note within soccer research assessing glycogen depletion that, as reported by Jacobs, Westlin, Karlsson, Rasmusson, and Houghton (1982), muscle glycogen concentration within eight Swedish top-level players was about 50% of the pre-match value

two days after a match. This illustrates the prolonged affect that glycogen depletion can have upon subsequent performance. Recent research in rugby league (Bradley et al., 2016) has, however, noted that professional players utilise 40% of their muscle glycogen stores during match play, regardless of the amount of carbohydrates consumed in the previous 36 hours. This notion would therefore support the view that muscle glycogen depletion does not have an influence upon fatigue presented. Nutritional intervention and the influence upon fatigue in the days post-match are researched further in Chapter 2.5.1.7 below.

Phosphocreatine (PCr) depletion has been a recent area of investigation within team sport settings (Bangsbo, Iaia, & Krstrup, 2007; Spencer, Bishop, Dawson, & Goodman, 2005). At exhaustion, ATP levels, which are rebuilt by the use of PCr, may be depleted, with athletes learning through experience to judge the optimal pace that ensures the most efficient use of PCr and ATP. Muscle glycogen is the primary source for ATP synthesis during team sport activities, and the experiences of fatigue, lack of energy or “emptiness” may be attributed to muscle glycogen depletion. In field based team sport settings, evidence for the contribution of PCr was noted by Gaitanos, Williams, Boobis, and Brooks (1993), who found that during ten 6 s sprints PCr contributed 50% of the ATP production in the first sprint and 80% during the tenth sprint, despite a significant decline in PPO by the fifth sprint. Evidence from the research by Gaitanos et al. (1993) shows that the majority of PCr re-synthesis is not complete within short recovery periods, similar to those associated with the intermittent nature of rugby union match play where passive rest periods are often not long enough to fully re-synthesise PCr.

The influence of glycogen depletion within team sport settings was further emphasised by Nicholas et al. (1999), where trained games players ingested a carbohydrate-electrolyte drink during fifteen minutes of intermittent running, with a 22% reduction in muscle glycogen utilisation recorded, thereby improving performance. During nutrient-related fatigue both slow twitch and fast twitch muscle fibres are influenced by glycogen depletion, and the individual muscle fibres most frequently recruited during that exertion are the ones that will become depleted of glycogen most rapidly. Typically during football based sports (soccer and rugby), fast twitch and slow twitch muscle fibres are used, yet the fast twitch fibres are recruited more frequently during high intensity efforts and therefore deplete more rapidly than slow twitch fibres. Fast twitch fibres are also noted to have a greater reliance upon glycogen (Wilmore & Costill, 1999). Due to the above mentioned depletion mechanisms, the fatigue sensations experienced may reflect muscle fibres’ inability to respond to the exercise demands. Refuelling and the role of glycogen within short and long-term recovery are examined in more detail in Chapter 2.5.1.7, and where the influence and relationship of recovery from fatigue are critiqued.

2.3.2.3.2 Metabolic by-products and fatigue

The most common by-product of fatigue is lactic acid, with its occurrence often appearing during high intensity muscular efforts, as often seen in rugby match situations. In research by Deutsch et al. (1998) forwards were noted to experience higher mean blood lactate concentrations than backs (6.6 vs. 5.1 mmol.l; $p = 0.063$). These values are similar to those reported in other team sports (Coutts et al., 2009) (5.59 ± 1.78 mmol.l), with the greater resultant by-products created during team sport match play emphasised, when comparing these values against those taken during periods of rest. At rest, a normal range for blood lactate was reported by Gollnick, Bayly, and Hodgson (1986) to be 0.5 ± 2.2 mmol.l, with similar rest values presented by Mazzeo, Brooks, Schoeller, and Budinger (1986) (0.33 ± 0.01 mmol.l). It is

important, however, for practitioners to note that the presence of lactic acid should not be blamed for the feelings of fatigue (Mann, 2007). Instead the process involves lactate accumulation, resulting in a condition called acidosis, due to a reduced capacity to buffer hydrogen ions. Acidosis, however, does not always mean that exercise is volitionally terminated, as athletes have been noted to exercise at a lactate level eight times greater than the resting value during semi-professional rugby league match play (Coutts, Reaburn, & Abt, 2003) (7.2 ± 2.5 mmol.l).

2.3.2.3.3 Neural fatigue and the excitation-contraction-relaxation processes

Another commonly reported factor that may be responsible for fatigue is the role of an athlete's inability to activate muscle fibres. This is perhaps the most common mechanism responsible for fatigue in the days after a rugby match, and lies within the excitation-contraction-relaxation (ECR) processes. The excitation-contraction-relaxation cycle within muscles involves action along the sarcolemma of the tubular system, with repetitive excitation of the muscle fibres, causing a progressive decrease in the trans-sarcolemmal gradients within the tubular system, which may result in a less negative resting membrane potential and decreased fibre excitability (Stephenson, Lamb, & Stephenson, 1998). There are many steps within the complex ECR cycle that can be seen as potential sites for muscle fatigue and are therefore of interest to sports science practitioners when assessing post exercise recovery rates. As noted within research by Stephenson et al. (1998) it is important to consider that the ECR cycle is less likely to be compromised during repeated contractions of slow-twitch muscle fibres and instead it is more likely that fast-twitch muscle fibres would reach a state of rigor first. The notion of low frequency fatigue (LFF) response created by game involvement associated with the ECR cycle, was first discussed by Edwards, Hill, Jones, and Merton (1977) and subsequently noted in recent research by McLean et al. (2010) to be a main contributor to fatigue in the days post-exercise. Both LFF and high frequency fatigue (HFF) result in reduced force production with LFF lasting for multiple days and HFF usually dissipating within two hours of the end of exercise (Raastad & Hallen, 2000). It is believed that these LFF responses are represented by perceived feelings such as "heavy legs" (Taylor, 2012), with SSC exercises such as vertical jumping being used to monitor long lasting low frequency fatigue. The role of the ECR cycle and the related neuromuscular fatigue research are examined in more detail in Chapter 2.3.3.

In a study by Kent-Braun (1999), assessing contributions to muscle fatigue in humans during sustained maximal effort (four minute maximum voluntary isometric contraction), it was noted that approximately 20% of muscle fatigue was attributed to central fatigue and that the remainder was associated with intramuscular factors. These intramuscular factors include metabolic responses from exercise, which are commonly seen in prolonged low intensity exercise situations, where failure of ECC is a reason for muscle failure. High intensity exercise, in contrast, involves accumulation of intramuscular metabolites as discussed in the peripheral fatigue section (Chapter 2.3.2.2). The contribution of central and peripheral fatigue can be estimated using electrical stimulated force measures, EMG and magnetic resonance spectroscopy (MRS).

2.3.3 Neuromuscular fatigue

2.3.3.1 Mechanisms of neuromuscular fatigue

Muscle fatigue concerns the decrease in performance capacity of muscles; usually evidenced by a failure to maintain or develop a certain expected force or power (Enoka & Duchateau, 2008).

As presented in Chapter 2.3.2, muscle fatigue can occur in two basic mechanisms: central and peripheral fatigue. Much of the recent research in NMF concerns peripheral fatigue, whereby local changes in the internal conditions of the muscle affect neuromuscular status. NMF has been described by McLellan et al. (2011b, p. 1030) as “any exercise induced reduction in the maximal voluntary force or power produced by a muscle, with the type of muscle contraction, intensity and duration of exercise being determining factors”. Models of NMF often refer to a reduction in the force or power production of a muscle, with few studies examining the relationship between neuromuscular function and rugby. As noted by Cairns, Knicker, Thompson, and Sjogaard (2005) the choice of model utilised depends upon the sport in question, with sometimes more than one model being needed to evaluate fatigue responses post-exercise. Two main theories exist around NMF including the central activation theory and the neuromuscular propagation failure theory (Allman & Rice, 2002), yet no ideal model that studies NMF exists (Cairns et al., 2005). As reported by Abbiss and Laursen (2005), central activation failure theory involves a reduction in neural drive, whereas the neuromuscular propagation failure theory sees fatigue as a result of reduced responsiveness and concerns peripheral mechanisms. This reduced responsiveness involves the ability of the muscle to produce force and is limited by the response of the muscle to an electrical stimulus. It is, however, important to note that the information presented on NMF by Abbiss and Laursen (2005) focused on cycling and not on an intermittent contact sport such as rugby, where eccentric muscle actions and blunt muscle trauma are the likely contributors to NMF. An important consideration for practitioners is that the central fatigue created by exercise could be a response to afferent input from peripheral organs, with the aim of preventing injury or death and resulting in a reduction or termination of exercise. Central fatigue and the related central governance theory are discussed below when considering the mental response of fatigue created in team sport settings.

Many studies (McLean et al., 2010; McLellan & Lovell, 2012; Mooney, Cormack, O'Brien, Morgan, & McGuigan, 2013; Twist et al., 2012) have followed the common trend of analysing NMF through Stretch Shortening Cycle (SSC) exercises, as opposed to isometric, eccentric and concentric movement patterns (Hoffman, Ratamess, & Kang, 2011; McLellan et al., 2011b). Strojnik and Komi (1998) noted that NMF mechanisms would vary between sub-maximal and maximal exercises, meaning that sport specific tests should be administered to assess NMF. The main difference between sub-maximal and maximal testing involves the intensity of the exercises prescribed; meaning that sub-maximal is often preferred within training settings as no further fatigue is added through the testing protocol. NMF fatigue and associated exhaustion experienced during or post maximal, or near-maximal, isometric contractions is unlikely to be a result of general depletion of the energy. Instead the likely cause of NMF, from a physiological standpoint, may be the high-energy phosphates, especially CP. During high intensity exercise the reduced rate of energy transfer from the stores to the ATP and CP cause an increase in muscle lactic acid. In research assessing muscle fatigue in sport by Asmussen (1979), it was reported that lactic acid production was termed as “fatigue substance”. This is therefore an additional area of consideration for practitioners utilising maximal NMF assessment within high intensity sporting activities.

2.3.3.2 Models of fatigue

Numerous linear models have been developed to explain fatigue, with a comprehensive model of the physiological responses to training stimuli being the fitness-fatigue theory (Figure 2.2).

This theory involves different training stresses resulting in different physiological responses (Banister, 1991). Early fitness and fatigue theory was developed by Banister (1975), who hypothesised that each training bout produced both a fatigue and a fitness impulse (Calvert, Banister, Savage, & Bach, 1976). Calvert et al. (1976) noted that fatigue decays three times faster than fitness, hence the need for positive training adaptation to enhance performance. The fitness or fatigue created can positively or negatively influence performance, resulting in a change following the stimulus and being dependant on the relative levels of both variables (Chiu & Barnes, 2003). Research (Hellard et al., 2006) has, however, proposed that the Banister model is inappropriate for use in monitoring the training process in elite swimmers, as the 5% Confidence Intervals (CI) values (the most useful parameters for monitoring training) were reported to be too wide. This view, which questions the irrelevance of the Banister model, is therefore a further consideration for practitioners, who need to be sure of its accuracy in order to make informed training prescription decisions.

In addition to the models of fatigue displayed in Figure 2.1, models of fatigue are examined in more detail in Table 2.12. It is, however, important to note that Table 2.12 includes many models to explain fatigue, but does not explain fatigue created as result of muscle damage from match demands. As noted within Chapter 2.1, the match demands for rugby union players involves many contact situations where muscle trauma damage is created alongside the muscle damage accumulated due to eccentric and concentric contractions (micro trauma). One could, therefore, argue that a muscle damage model should be proposed when assessing the possible fatigue causes associated with rugby union. Inhibition, due to the swelling that could occur with muscle damage created by moments of physical contact from training and games, will affect neuromuscular stimulation and therefore subsequent performance test results, despite players perhaps not presenting as being fatigued in other performance measures (Smith, Kruger, Smith, & Myburgh, 2008). In the review of models of fatigue by Abbiss and Laursen (2005), which focused upon the sport of cycling, they correctly identified Types 1, 2 and 3 muscle damage categories, with Type 1 muscle damage encompassing swelling as a result of exercise. This Type 1 muscle damage, proposed within the research by Abbiss and Laursen (2005), does, however, not involve trauma experienced by body contacts associated with many team sports such as rugby. Despite some research showing the effect of deliberate muscle damage imposed on animals in the laboratory settings (Bunn et al., 2004; Rushton, Davies, Horan, Mahon, & Williams, 1997), to the author's knowledge there are no studies that have been published in rugby union illustrating the effect of muscle damage from trauma, on general fatigue. This, though, is unsurprising considering the ethical issues that surround all research in humans.

Table 2.12: Exercise fatigue models and the theories associated with them

Model	Theory	Additional points
The cardiovascular/anaerobic model	<ul style="list-style-type: none"> Performance is determined by capacity of the heart with training increasing cardiovascular fitness The heart has a limiting maximum cardiac output that is reached at the onset of a “plateau phenomenon” Instead when the oxygen supply becomes inadequate, it is probable that the heart by human design includes controls to protect the heart from ever entering dangerous situations 	<ul style="list-style-type: none"> The capacity of the heart does not limit oxygen utilisation by the exercising skeletal muscle, therefore this theory is limited Instead the heart reaches the limit of its powers earlier than the skeletal muscles, and determines capability for exertion A “governor” exists in the central nervous system, whose function is likely to prevent the development of myocardial ischemia
The energy supply model	<ul style="list-style-type: none"> Fatigue during high intensity exercise results from the inability to supply ATP at rates sufficiently fast to sustain exercise Superior performance occurs when a greater capacity to generate ATP in the specific metabolic pathway(s) is developed Exercise is terminated by a central governor responding to factors other than skeletal muscle pH 	<ul style="list-style-type: none"> ATP concentrations are “defended” in order to prevent the development of skeletal muscle rigor Evidence suggests that cell ATP rarely falls below 70% of the pre-exercise level, even in cases of exercise fatigue Peripherally located inhibition of muscular contraction is key to exercise cessation
The energy depletion model	<ul style="list-style-type: none"> The energy depletion model of exercise performance is specific for exercise lasting more than 2-3 hours The human body has a limited capacity to store carbohydrates Fatigue during prolonged exercise is associated with depletion of muscle glycogen stores 	<ul style="list-style-type: none"> The influence of central (neural) fatigue limiting prolonged exercise when muscle glycogen concentrations are low is unclear Delaying the onset of terminal muscle glycogen depletion will aid performance
The muscle recruitment (central fatigue)/muscle power model	<ul style="list-style-type: none"> The processes involved in skeletal muscle recruitment, excitation and contraction is the limiting factor Reduced central neural drive to muscle after fatiguing muscle contractions 	<ul style="list-style-type: none"> The brain concentration of serotonin (and perhaps other neurotransmitters, including dopamine) alters the density of the neural impulses reaching the exercising muscles, thereby influencing fatigue rate
The biomechanical model	<ul style="list-style-type: none"> The greater the muscle’s capacity to act as a spring, the less torque it must produce and hence the more efficient it is 	<ul style="list-style-type: none"> The more economical the athlete, the faster they will be able to run before reaching a limit Reduced tolerance to muscle stretch and a delayed transfer from muscle stretch to muscle shortening in the stretch/shortening cycle
The psychological/motivational model	<ul style="list-style-type: none"> The ability to sustain exercise performance results from a conscious effort and is often included as a component of central fatigue 	

2.3.4 Factors affected by fatigue which are important for performance

An athlete's current training status has a large effect upon the mechanism of fatigue experienced during match play, yet interaction between mechanisms is often seen as a major contributor, as was reviewed in research by Knicker et al. (2011). Data from rugby league (Kempton, Sirotic, Cameron, & Coutts, 2013) assessing match-related fatigue during elite rugby league match-play, noted reductions in physical performance towards the end of matches, following brief periods of intense exercise. Kempton et al. (2013) also noted that match-related fatigue during elite rugby league match play, showed significant reductions in skill rating and the number of involvements observed in the final stages of matches, which may be attributable to match-related fatigue. Within soccer, recent research by Krstrup, Zeris, Jensen, and Mohr (2010) reported that decrements in distance covered by sprinting and high-speed running toward the end of elite female soccer games are caused by fatigue. Development of fatigue during soccer match was also examined by Mohr et al. (2003), with fatigue reported as occurring towards the end of matches, as well as temporarily during the game. Additionally, within the research by Mohr et al. (2003) the top-class players were noted to perform better (11%; $p < 0.05$; 2.26 ± 0.08 km) on the Yo-Yo intermittent recovery test than the moderate players (2.04 ± 0.06 km), despite the top-class players performed 28% and 58% more ($p < 0.05$) high-intensity running and sprinting. Lastly, within soccer, evidence for the effect of fatigue upon game performance was also noted by Greig (2008), when assessing isometric torque of the knee flexors and extensors, with peak eccentric knee flexor torques at the end of the game (127 ± 25 N.m) compared to the first fifteen minutes (161 ± 35 N.m, $p = 0.02$).

2.3.5 Assessing fatigue

When monitoring fatigue, it is important to consider that fatigue occurs in the nervous system and muscle at varying levels, and the rates at which fatigue develops depends on the activity and intensity of the sport completed. Neuromuscular function tests are perhaps the most commonly used forms of assessing player fatigue in team sport settings and include: varying forms of jump tests; plyometric push-ups; sprint performances; sub-maximal (such as heart rate recovery tests) and maximal performances; and isokinetic dynamometry (Duffield et al., 2012; Johnston et al., 2013; Twist & Sykes, 2011). In this review of best practice for assessing fatigue, Taylor (2012) observed that 91% of high performance programs reported using some form of monitoring, with the predominant usages being injury prevention (29%), monitoring effectiveness of the training program (27%), maintaining performance (22%) and preventing overtraining (22%). Considering the research above, which illustrates the accumulation of fatigue and incomplete recovery commonly seen in rugby, the importance of further emphasis on optimising post-match recovery periods is noted, in order to avoid additional cumulative adverse effects on games and training.

Few studies have used monitoring methods that prescribe future training, instead previous research has focused on adaptation to training load (Aubert, Seps, & Beckers, 2003; Hartwig, Naughton, & Searl, 2009) and on the existence of overtraining (Halsen & Jeukendrup, 2004). One study that has implemented measures to assess deliberate overreaching in Rugby League players over a six week progressive overload period (Coutts, Reaburn, Piva, & Rowsell, 2007), noted that no single reliable biochemical marker was present and also that the Multistage Fatigue Test (MSFT) test may be a useful measure for monitoring responses in team sport athletes. Coutts, Reaburn, Piva, and Murphy (2007) concluded that muscular strength; power and endurance were reduced following the overload training period, indicating a state of

overreaching. Resting measure of plasma testosterone to cortisol ratio, plasma glutamate, plasma glutamine to glutamate ratio and plasma CK activity demonstrated significant changes at the end of the overload training period ($p < 0.05$). The decreased performance in tests such as the MSFT and 3RM exercises, were most likely a result of increased muscle damage caused from a decrease in the anabolic-catabolic balance. Laboratory methods for assessing NMF are more complex, more time consuming and more invasive than measures typically used within elite sport settings. A direct summary of the athlete's neuromuscular status has been the aim of practitioners for many years, with reaction tests and jump tests being some of the most used protocols (Waldron et al., 2011).

A recent area of interest for practitioners has been the use of subjective indicators of well-being and electronic devices to assess overall readiness, which, when combined with more traditional measures of NMF have presented added value (Flatt & Esco, 2013, 2015; Tian et al., 2013). Readiness, assessed by bio-electrical current which is painless and simple to administer is becoming an appropriate alternative for practitioners, with direct electronic assessments of NMF via devices such as *Check, ithlete* and *Omegawave* being readily used. Subjective indicators and profile of mood states (POMS) questionnaires have been used in recent research (Filaire, Bernain, Sagnol, & Lac, 2001; Halson et al., 2002). Despite being sensitive for daily use when combined with more traditional measures to assess NMF (Schmikli, Brink, de Vries, & Backx, 2011), their accuracy has been questioned (Grove & Prapavessis, 1992). Modern practices designed consistently to produce valid neuromuscular status utilising NMF testing via recent technological advances, are key areas of future development. Despite the fact that the use of well-being and electronic devices that assess overall readiness do not actually assess NMF, the functional state assessment that these modern practices investigate is still of interest to practitioners. In contrast to performance tests, which are more objective in nature, such functional state assessments do not involve any potential influence of athlete compliance and therefore participants cannot manipulate data produced. Removing any objective discrepancies that can be associated with common NMF testing practices, such as lack of motivation from athletes, is key, when considering the effect compliance issues of players could have upon results.

In a critical appraisal of monitoring tools to assess recovery, Twist and Highton (2013) noted that match demands of rugby league lead to immediate and prolonged post-match fatigue, due to a combination of muscle damage and substrate depletion. When assessing perceptual measures, biochemical markers and muscular function, Twist and Highton (2013) noted a simple measure of muscle function such as jump testing to be the most practical and appropriate method of determining the extent of fatigue experienced by rugby league players. Reduced performance during peak knee extension torque testing was reported to be prolonged by Twist and Sykes (2011) for up to 48 hours post simulated rugby league game; with West et al. (2014) also reporting prolonged performance reduction when assessing peak power output from CMJ for up to 60 hours post rugby union game. Despite the fact that the research by Twist and Sykes (2011) incorporated many measures of performance (perceived muscle soreness, Creatine Kinase [CK] activity, isokinetic strength and jump height) the Rugby League Match Simulation Protocol (RLMSP) involved within this study along with the low playing level of the participants, make this research limited in value to other elite rugby union researchers. The research by West et al. (2014), by contrast, incorporated assessment of professional rugby union players post real match situations and involved the use of saliva and force plate testing

(lower body peak power output). Results showed, reduced NMF and hormonal disruption at 36 hours post match, before recovering at 60 hours post-match, while self-perceived reduction in mood was noted to have recovered by 36 hours post-match. It is, however, important to note that the differing time point assessments and methodological involvement mentioned above, within these two studies, could perhaps explain the differences revealed. Regardless of the method used to assess NMF, it is important to note that heavy training of the lower body has been advised to be avoided in the 48 hours after a rugby league game (McLellan et al., 2011b). The reliability of NMF testing is difficult to ascertain, as no study has compared methods across research, meaning that comparisons between research and results are limited.

2.3.6 Fatigue and rugby

Research on player fatigue levels in rugby is commonly reported (Alaphilippe et al., 2012; Kempton et al., 2013) and the associated phenomenon of burnout is a concern within the modern game (Cresswell & Eklund, 2006). Within rugby union, the myriad of factors that can effect fitness or fatigue (minutes played, injury, weather and playing style) created by training and games, means that the Banister model is unlikely to be accurate and potentially difficult for practitioners to control. Fatigue is often represented by the inability to maintain force or power output at the required level and as noted by Halson (2014), fatigue is multifaceted in nature and can be influenced by the type of stimulus, contraction, duration, frequency and intensity of the exercise. Due to these activities and the large volumes of activity from both training and games over the course of a playing season, rugby players become fatigued (Argus, Gill, Keogh, et al., 2012; Cresswell & Eklund, 2006; Fuller, Brooks, Cancea, Hall, & Kemp, 2007). The most commonly used fatigue models and the theories that surround them are reviewed in Table 2.12, with notes taken from Noakes (2000). When considering the models above, it is clear that all the models contribute to the fatigue response developed from exercise and that, within rugby, a fatigue response is likely to be created by a combination of all models critiqued above.

Uncertainty exists around the influence of rugby specific impacts and muscle damage on acute NMF and associated recovery post-match play in rugby union. To date, the majority of research in rugby union and players readiness has focused upon movement patterns during games (Cahill et al., 2013), training workload (Casamichana, Castellano, Calleja-Gonzalez, San Roman, & Castagna, 2013) and performance fatigue markers (Coutts, Reaburn, Piva, & Rowsell, 2007; Coutts, Slaterry, & Wallace, 2007) all of which would better prescribe future training. As seen in the study by McLellan, Lovell, and Gass (2011a), PRFD on average was 12653 N.s⁻¹ across rugby league players 24 hours pre-game and on average 9379 N.s⁻¹ 24 hours post-match. Similarly, McLellan and Lovell (2012) noted reductions in peak power of -10% for up to 24 hours post rugby league game, before recovering at 72 hours. Additionally, in another study assessing rugby league players (McLean et al., 2010), CMJ flight time and relative power were significantly reduced in the 48 hours following the match. McLean (2010) reported that CMJ variables returned to near baseline values four days after matches, while West et al. (2014) noted peak power measured via CMJ recovered no sooner than 60 hours (-7% for 36 hours). McLean et al. (2010) noted that day one CMJ flight time measures were significantly lower than day four ($p < 0.01$, $d = -1.06$) and the day before the match at the end of the training microcycle ($p < 0.05$, $d = 1.06$), with West et al. (2014) noting NMF assessed by CMJ outlasting mood disturbances post rugby union match. McLean et al. (2010) noted that CMJ values have been shown to be reliable and useful in detecting LFF in team sport athletes, with this notion supported by many other researchers (Cormack, Newton, McGuigan, & Cormie, 2008; Cormack, Newton, McGuigan, &

Doyle, 2008). It is, however, important to note that the load prescribed for CMJ needs to be carefully selected, as under a load LFF is less influenced due to the relationship that exists between load lifted and RFD (McLellan, Lovell, & Gass, 2011d).

Research by Fowles (2006) showed CMJ flight time to be sensitive to acute fatigue and CMJ relative power to be more sensitive to accumulated fatigue. This notion was also supported by Johnston et al. (2013), who noted increased Type 2 muscle fibre disruption and the resultant changes in the force-velocity relationship. Contrasting results do, however, exist showing a lack of sensitivity of jump height to fatigue (Cormack, Newton, & McGuigan, 2008; Coutts, Reaburn, Piva, & Rowsell, 2007). It is important for practitioners to note that movement with minimal loading on the muscles, such as a CMJ performed at bodyweight, may be impaired to a lesser extent than those that involve maximal loads, such as isometric strength tests, which rely on maximal force production instead, as reported by Twist and Sykes (2011). Prescription of CMJ as a testing measure does, however, have limitations, including technique and apparatus used (Glatthorn et al., 2011; Markovic, Dizdar, Jukic, & Cardinale, 2004). However, this notion that CMJ testing is an unreliable measure for fatigue testing was disputed by Twist and Sykes (2011) and supported by other research (Hamilton, 2009; McLellan & Lovell, 2012), which showed jumping activities to be reliable and accurate in determining neuromuscular fatigue post-match situations and in aiding the fatigue-recovery cycle time line. Jump testing is critiqued in more detail within Chapter 2.4.1.2, showing its relevance as a performance test and as a measure of fatigue.

Accumulation of fatigue and incomplete recovery post rugby game has been reported by many authors (McLean et al., 2010; McLellan & Lovell, 2012; West et al., 2014), with neuromuscular function, biochemical, endocrine and perceptual measures used as markers of fatigue. Despite a vast amount of research upon fatigue post-match, few studies have researched the efficiency of methods for monitoring restoration of performance and overall recovery between games in elite rugby settings, where players are competing on a weekly basis (Taylor, 2012; Twist & Highton, 2013). Both McLellan and Lovell (2012) and McLean et al. (2010) utilised CMJ as a test of NMF, reporting compromised values (flight time, peak power, peak rate of force development and peak force) for up to 48 hours post-match. Similarly, West et al. (2014) noted reduced NMF in conjunction with hormonal disruption, for up to 36 hours post-match. Cumulative fatigue over a season has also been reported by Gill, Beaven, and Cook (2006) and was illustrated by the elevated CK levels pre-match. Although varying degrees of muscle damage can alter CK levels, residual fatigue carried over from the previous match and the training schedule that followed that match can also have an effect upon the muscle damage present and the associated CK levels reported. Often throughout training weeks (microcycles) in team sports, players are required to return to training in the immediate days post-match, as the preparation for the next match needs to commence, yet the consequence of these training sessions are an important consideration for practitioners. Training stress cannot be underestimated, considering the evidence that a typically used strength and power session resulted in reduced NMF for 48 hours post exercise (Gee et al., 2011), represented by reduced CMJ height (3-10%) and increases in CK levels (2 hours: 210 ± 57 U/L, 24 hours: 413 ± 205 U/L, 48 hours: 205 ± 50 U/L) compared to baseline levels baseline (145 ± 54 U/L).

Significant correlations have been reported between the total number of severe impacts (> 10.1 G) that rugby players are exposed to, their peak rate of force development (PRFD) and their peak power (PP) values post-match (McLellan & Lovell, 2012), with Twist and Sykes (2011)

showing evidence of exercise induced muscle damage (EIMD) for up to 48 hours post simulated rugby league game. McLellan and Lovell (2012) assessed twenty-two elite male rugby league players, over eight games, using GPS technology (pre and post-game), in order to compare changes in variables when assessing neuromuscular responses to impact and collisions during match play. Data from the study by McLellan and Lovell (2012), demonstrated that neuromuscular function is compromised for up to 48 hours post-match, indicating that at least two days of modified activity is required to achieve full neuromuscular recovery after elite rugby league match play. Similarly, research within rugby league by Johnston et al. (2013) reported that cumulative fatigue from rugby league matches results in compromised high speed running, accelerations and tackling, thus illustrating the intensity of games. The research by Twist and Sykes (2011), in contrast to both McLellan and Lovell (2012) and Johnston et al. (2013), assessed muscle damage post simulated match situation using differing measures of neuromuscular function (CK values and knee extensor torque). They perceived soreness measures, and suggested recommendations for adapted training in the 48 hours following a game. Results from a similar study in rugby union, assessing neuromuscular function throughout a season, showed an increase in CK levels during the first three to five weeks of the season, followed by a stabilisation (Alaphilippe et al., 2012). Within another rugby union study, assessing changes in strength and power throughout the competitive phase of a season (Argus et al., 2009), it was noted that decreases in power were due to compromised physical development caused by fatigue from weekly competition and training stress.

Data from Alaphilippe et al. (2012) and Argus et al. (2009) demonstrate the need for regular monitoring of both biochemical and neuromuscular markers, in order to enable effective management of fatigue throughout a competitive season. The difference between physical, biochemical and endocrine time-course of recovery post rugby game, have been illustrated by research presented by McLellan et al. (2011b), which noted that the biochemical markers do not reflect the changes in performance over the same time period. In addition, positional effect upon restoration time-course, was noted in a study assessing physical demands of rugby union and the associated fatigue (Mashiko, Umeda, Nakaji, & Sugawara, 2004b), where it was noted that both physical (biochemical markers) and mental (Profile of Mood States POMS) measures differed post-match and across playing positions. This research by Mashiko, Umeda, Nakaji, and Sugawara (2004a), however, only involved thirty-seven university standard players, post a single game, therefore limiting its relevance and comparability to elite rugby union.

Considering the aforementioned positional demands involved in rugby (backs and forwards) and the differences in fatigue response (EIMD, reduced functional performance measures), post-match are of no surprise. As reported by Mashiko et al. (2004b), rugby union backs display movement patterns that are more focused on high speed running and tackling, compared to rugby union forwards who take part in running, tackling and an element of mauling and scrummaging involving physical contact. Although data taken from rugby league cannot be directly compared to rugby union, it is of interest to note that Twist et al. (2012) reported that forwards showed greater perception of muscle soreness in the immediate two days post-match which could be explained by the greater number of contacts experienced by forwards. Similarly, as reported by Mashiko et al. (2004b), the blunt trauma associated with forward play may produce longer lasting muscle damage than that experienced from eccentric actions, which backs would be more likely to encounter, due to their greater number of decelerations and accelerations completed within game situations compared to forwards (Twist et al., 2012).

When considering the fact that forwards play less time and cover less distance than backs (yet experience longer muscle damage), the damaging effect of the blunt force trauma that forwards experience is further emphasised. Recent data from rugby union (Jones et al., 2014), supports the view that the number of impacts encountered during a match relate specifically to the levels of muscle damage (CK) experienced. Additionally, Jones et al. (2014) reported that high speed running was a predictor of muscle damage for backs, with tailored individual recovery strategies, based upon impacts and high speed running data derived from GPS, being of interest.

The research assessing muscle damage post rugby involvement (Mashiko et al., 2004b; Takarada, 2003; Twist et al., 2012) is of significant relevance to practitioners and it could be argued that tailored recovery strategies, based upon positional demands (utilising GPS data), would provide a better understanding of fatigue post-match. It is also of note, in the study by Twist et al. (2012) in professional rugby league, that backs presented greater decrement in performance compared to forwards, when assessing changes in CK, perceptual and neuromuscular fatigue for up to 48 hours post-match. Data from previous research (Cunniffe et al., 2010; Smart, Gill, Beaven, Cook, & Blazeovich, 2008; Takarada, 2003), also reported positive correlations between the number of tackle involvements during a rugby union match and CK, suggesting that tissue damage is proportional to the number of body contacts a player experiences and therefore related to position played. Further evidence of match contacts experienced and resultant fatigue was noted by Twist et al. (2012), where total contacts for forwards was reported to correlate with all markers of post-match fatigue ($p < 0.05$) ($r =$ muscle soreness 0.62; perceived fatigue 0.69; CK 0.74; jump flight time -0.55), but only flight time was correlated with offensive contacts in backs ($p < 0.05$) ($r = 0.54$).

Decrement in performance measures (CMJ flight time) for backs compared to forwards could be associated with the muscle damage common from eccentric lengthening actions and the effect this has upon the stretch-shortening cycle utilised in jump testing protocol. A LFF measurement, has been noted as an important variable in measuring NMF (Fowles, 2006), with the causes of LFF being different to that of HFF. LFF is commonly seen post heavy training periods and involves impairment in excitation contraction coupling, due to microscopic muscle damage from eccentric muscle action, as opposed to HFF, which involves impaired action potential propagation over the sarcolemma (Jones, 1996). When associated within a game context, LFF is typically illustrated by reduced jump performance in backs and may be due to the increased number of accelerations and decelerations involved in backs' play, compared to forwards. However, Twist et al. (2012) argued that more decelerations could be seen in forwards during games as they approach contact situations, compared to backs, who would experience less contact situations. Despite the quantification of decelerations into contact not being categorised within the methodology proposed by Twist et al. (2012), this is an area that warrants further investigation. The significantly greater ($p < 0.05$) number of contacts for forwards compared to backs (38.2 ± 18.7 ; 25.2 ± 8.0), could have been attributed to increased muscle damage and perception of fatigue. The research presented above highlights the importance of looking at the relationships between high level impacts ≥ 7 G rather than total impacts, as the muscle damage response created from impacts are likely to be predominately as a result of high level impacts. Impacts, therefore, above a certain level could act as measurement tool for future research. However, the reliability and protocol involved in utilising GPS impacts as a monitoring tool, used to guide training prescription in post-match situations, also needs further examination.

2.3.7 Restoration of Performance

Research showing incomplete restoration between bouts of exercise is vast, with Ronglan et al. (2006) observing reduced 20 m sprint time and CMJ performance during a handball tournament and Kraemer et al. (2001) noting insufficient restoration of maximal strength throughout a wrestling tournament. Planned periodisation, without consideration for restoration of performance and testing of time-course of recovery is likely to put players at risk of sub-optimal performance, or more seriously injury. Rugby union has been reported to involve both intense anaerobic exercise, interspersed with lower intensity bouts of aerobic exercise (Cahill et al., 2013). Due to these activities and the large volumes of activity from both training and games over the course of a playing season, rugby players become fatigued (Argus, Gill, Keogh, et al., 2012; Cresswell & Eklund, 2006; Fuller et al., 2007).

In research by Gill et al. (2006), assessing the effectiveness of four recovery interventions upon the rate and magnitude of muscle damage recovery of twenty three elite rugby players, it was noted that muscle damage was carried over from previous games and/or training, as represented by CK levels, with increased levels of fatigue present as the rugby season progresses. As also noted by Gill et al. (2006), the greatest physical stimuli of a rugby players week is frequently the match, although high training loads combined with match exertions and insufficient recovery in rugby have been reported which often push players into states of overreaching (Coutts, Reaburn, Piva, & Murphy, 2007). The need to recover between games and to restore performance prior to subsequent training sessions in the intervening periods is of major importance within professional team sports. The risk of injury or sub-optimal performance, resulting from insufficient recovery are points to consider for practitioners, while also considering the accumulation of training and/or non-training stress. As noted by Kreider et al. (1998), overreaching (OR) is an accumulation of training and/or non-training stress, resulting in a short term decrement in performance capacity, in which restoration of performance capacity may take from several days to several weeks. An accumulation of training stress, if managed properly, will have a positive effect upon the athlete. However, if managed poorly and insufficient recovery occurs, overreaching can develop into the more severe training response phenomenon of overtraining.

Long-term decrement in performance capacity is the result of imbalance between training and recovery; this is known as overtraining (OT). OT lies at the end of the training stress continuum, and occurs if training is not prescribed according to the recovery requirements of athletes (Halsen, Lancaster Jeukendrup and Glessen, 2002). Stress on athletes' bodies in team sports is often more frequently accumulated by game situations where players are asked to compete on a weekly basis. As hypothesised by Twist et al. (2012), from their post-match fatigue research in rugby league; team sport practitioners should pay specific attention to the 24 hours post-match, as this is the most challenging period in terms of training prescription between games. OT and overreaching has been recognised as a significant problem in many sports, including rugby union and has been regularly researched (Coutts, Reaburn, Piva, & Murphy, 2007; Coutts, Reaburn, Piva, & Rowsell, 2007; Halsen & Jeukendrup, 2004; Wallace, Slattery, & Coutts, 2009). Applying the appropriate training volume presents a major problem for many coaches aiming to achieve optimal sporting performance with their athletes. More recent discussion of OT (Lewis, Collins, Pedlar, & Rogers, 2015), has raised the notion of unexplained underperformance syndrome, yet no research to support their views currently exists. The term unexplained underperformance syndrome, related to a period of unexplained

underperformance, whereby fatigue is persistent and maladaptation to the training programmes implemented likely to have occurred. It could be argued that it is perhaps unlikely that this notion of unexplained underperformance syndrome would be explained in the near future, as despite its relevance to the more commonly researched phenomenon of OT, the exact nature of this syndrome is unknown. Unexplained underperformance syndrome is expected to involve many of the mechanisms and likely causes associated with OT, yet the multifactorial nature of the construct to which unexplained underperformance syndrome involves means that it cannot be explained by an imbalance between training and recovery.

When assessing activities to be performed in the days post rugby match, Twist and Sykes (2011) discussed that activities performed should be selected carefully. Twist and Sykes (2011) noted that resistance training, involving maximal strength emphasis, should be avoided in the 48 hours post-match, as this has been reported to increase chances of injury. McLellan et al. (2011b) did, however, note in their study of rugby league players that PRFD values were accelerated post-match, when resistance training was implemented in the days post-performance. PRFD is commonly used as measure of explosive strength. When testing fatigue following a game of rugby that involves many activities of an explosive nature, PRFD is therefore considered an appropriate measure to monitor fatigue in rugby specifically. A reduction in PRFD post-match situations in team sports has also been reported in soccer (Thorlund, Aagaard, & Madsen, 2009), yet not in a study by Hoffman et al. (2011) involving American football players. McLellan et al. (2011b) noted that these contrasting PRFD values, noted by Hoffman et al. (2011), may be explained by the reduced total number of contacts and the protective padding worn in American Football. In rugby league, significant NMF has been reported to be highly dependent upon the number of heavy collisions > 7.1 G (McLellan & Lovell, 2012).

2.3.8 Recovering from team sport activities

Fatigue can be both short term (recovering within hours or days of exertion) or longer-term, where longer term fatigue is considered abnormal. Distinct durational phases of fatigue have been noted by many authors (Halsen & Jeukendrup, 2004; Meeusen et al., 2013; Schmikli et al., 2011; Tian et al., 2013), with various theories discussed, including functional overreaching (FOR), non-functional overreaching (NFOR) and OT. FOR can be considered a required practice for inducing adaptation within the athlete (planned and managed by the coach) and is commonplace in many elite sport settings. NFOR, by contrast, involves poor management of fatigue levels and when occurring needs an alteration of training load and training plan so as not to induce any further negative adaptation. OTS develops when long-term decrement in performance capacity exists as a result of imbalance between training and recovery and is a consequence of not reacting to NFOR signals. Due the multifaceted nature of fatigue, its monitoring or measuring is complex, meaning that providing accurate reasons for changes in performance or assessing athlete readiness are difficult. Many coaches monitor load retrospectively, not only in order to assess the load-performance relationship, but also to enable future planning and thereby reduce the risk of injury and NFOR.

Recovery post-exercise covers many facets of performance and is a broad term referring to restoration of performance capacity, often with both short-term and long term processes post-exercise referred to as recovery. After a workout one is fatigued and performance capacity is reduced, and in the hours and days after the workout one “recovers” with performance capacity

returning to normal within this short-term time-course. The time-course of recovery associated with a training session depends on many factors, including how hard the workout was, with, intensity, duration, player capacity and environmental factors, such as altitude and heat, playing major roles in the speed at which players return to pre-performance values. Acute or rapid recovery post-exercise is different from long-term adaptation and associated fitness fatigue models, with long-term adaptation referring to the improvements in the muscle and cardiovascular system that will ultimately result in improvements in performance. Often research discussing recovery refers to rapid recovery in the hours after exercise and sometimes refers to the longer-term effects. Both short and long term recovery are linked, but they are not the same. Short-term recovery typically lasts for 2-3 mins, involving rapid decline of VO_{2max} and being more related to intensity of exercise rather than duration. During short-term recovery an elevated metabolic rate is present: to reduce core body temperature; provide O_2 for energy cost; replenish glycogen and remove lactate. This research investigates the longer-term period of recovery in team sport athletes between games and across playing seasons, thereby examining restoration of performance time-course and performance markers that can be used to assess this longer term recovery period.

Within team sport settings, perhaps the most important aspect of athlete preparation during a competitive season is recovery between weekly games, with the extent of the recovery required being determined by the volume and mechanisms experienced. The mechanisms of EIMD can be mechanical, metabolic or oxidative, with all of these mechanisms evident within a contact sport like rugby and due to blunt force trauma, distances covered and acceleration and decelerations encountered (Alaphilippe et al., 2012; Johnston et al., 2013; McLean et al., 2010; McLellan & Lovell, 2012; McLellan, Lovell, & Gass, 2010; McLellan et al., 2011a, 2011b; Twist & Sykes, 2011; West et al., 2014). The metabolic and mechanical costs created by EIMD, mean that muscular function is impaired for up to 48 hours, yet the stress exerted upon muscles is considered to be an important trigger required for adaptation to occur (Twist & Eston, 2009). Recent research by Minett and Duffield (2014), assessing the role of both central and peripheral factors affecting recovery, suggested that the potential for other drivers of recovery outside of peripheral factors (muscle damage or metabolic) could be of similar importance. Despite the role of the brain as a contributor to neuromuscular recovery (as required following competition and training) remaining unclear, the elements associated with central fatigue are obvious when considering the influence of CNS in motor unit recruitment during exercise. It is agreed that much of the reduction of peripheral fatigue from recovery strategies is attributed to recovery of the brain (Gandevia, 2001), with a psychobiological model discussed by Smirmaul, Bertucci, and Teixeira (2013), when assessing the paucity of VO_{2max} testing being maximal. Practitioners are advised to consider recovery to be a multifaceted process (De Pauw et al., 2013). However, current methods of assessing neurophysiological measures [computed tomography (CT), magnetic resonance imaging scan (MRIS) and electroencephalography (EEG)] limit its appeal for practitioners in the elite field, due to logistical and budget restrictions. Developing an understanding that post-exercise recovery practices should not solely focus upon peripheral mechanisms of fatigue is key. Further research in the area of recovery strategies that impact the brain are needed to understand better current methods that would minimise brain fatigue and ultimately improve performance (Minett & Duffield, 2014).

Kellmann (2002) described recovery as the compensation of fatigue and/or decrease in performance that is a tendency to stabilise in the internal environment of the athlete. Recovery

is a term used to describe both positive and negative adaptations to the workloads that athletes are exposed to from training and competition. Positive adaptation involves restoration and regeneration of both physical and psychological capabilities, whereas negative adaptation involves a failure to recover from training and competition. Practitioners, in both the elite and amateur fields, need to help athletes create a healthy balance between training hard and recovering well in order to ensure optimal performance. The principle of recovery (from a single session) as displayed in Figure 2.2 is considered one of the basics of training, yet is one that is often ignored by athletes and coaches (Rushall & Pyke, 1990). Recovery and adaptation from exercise are essential for optimising performance, with adaptation considered to be the process of adjustment to a specific stimulus. Repeated stimuli are implemented within a team sport athlete's season and periodisation is a method for employing sequential or phasic alterations in the workload, training focus, and training tasks contained within the microcycle, mesocycle, and annual training plan (Baker, 1998). As reported by Baker (2007), a periodised training plan within team sports encompasses a properly designed framework for appropriate training, so that training tasks, content, and workloads are varied at a multitude of levels and in a logical, phasic pattern in order to ensure the development of specific physiological and performance outcomes at predetermined time-points.

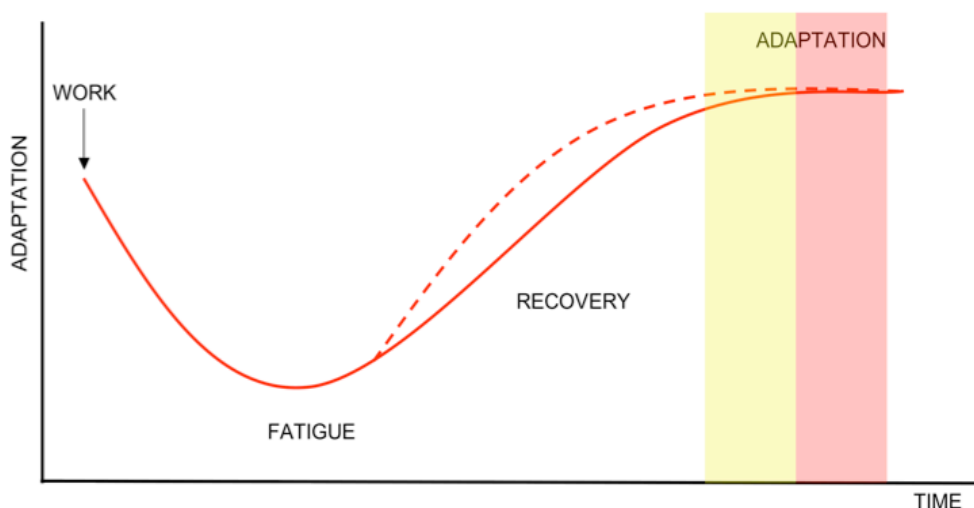


Figure 2.3: Training adaptation theory adapted from Bompa and Haff (2009)

The ability of athletes to recover from weekly competition in team sport enables them to be able to train sooner and with better quality, therefore improving the chances of success in the next competitive match. The goal of many practitioners working within team sports is to restore players to pre-game levels and in the shortest possible time, therefore minimising the aforementioned sources of fatigue created by game play and training sessions. Training stimulus responsiveness is an area that practitioners should pay attention to within their rugby players, as inappropriate loads can result in players being ill prepared and in a sub-optimal state to perform pre-game. When considering that the individual variation in both physiological and psychological responses from training and games are varied across playing populations (Elloumi, Maso, Michaux, et al., 2003; Hartwig et al., 2009), the need to manage the individual training dose is emphasised. The dose of training given to players is only effective if the individual responsiveness to the load applied is considered and acted upon, in future sessions, if

need be, in order to enable optimal performance. With this individual variation in mind, it is important for practitioners to prescribe the appropriate training session at the correct point in the training week, as both field based sessions and gym based sessions (as explained in Chapter 2.2.2.1) impose varying responses upon athlete fatigue levels and therefore subsequent varied restoration of performance post-match.

Evidence above in Chapter 2.2 illustrates the commonality of gym-based sessions within rugby teams weekly training schedules and the benefit such sessions have for improving subsequent performance are well documented (Argus et al., 2009; Baker, 2001b, 2001c; Beaven, Cook, et al., 2008; Comfort, Haigh, & Matthews, 2012; Pienaar & Coetzee, 2013). The resultant effect of training sessions (both field and gym) in the days between games has produced a large amount of research to date (Coutts, Reaburn, Piva, & Murphy, 2007; Crewther et al., 2013; Cross, Williams, Trewartha, Kemp, & Stokes, 2015; Edmonds, Sinclair, & Leicht, 2013; Elloumi, Maso, Robert, Michaux, & Lac, 2003; Gaviglio & Cook, 2014; Twist & Highton, 2013), with the physiological and psychological response created as result of these training sessions being apparent. Due to the extensive length and intensity of a professional rugby playing season, alongside the aforementioned individual fatigue response created by training, the practitioners' knowledge of the effect of specific training sessions upon players fatigue levels is key. Research by Howatson, Brandon, and Hunter (2016) illustrated the influence of specific resistance training sessions upon recovery in elite track and field athletes, where, in the immediate hours post-match, increased lactate values post strength training in comparison to power sessions were noted. Additionally, impairment in maximal strength on the day post strength training was noted, therefore illustrating the neuromuscular and endocrine response associated with varying training stimuli.

Recent research by Cook, Kilduff, Crewther, Beaven, and West (2014) illustrated the influence of varying training sessions upon subsequent performance, showing a decrease in salivary testosterone concentrations in the afternoon, following a morning speed session (-6.2 ± 7.1 pg ml^{-1}), in contrast to a weights session (-1.2 ± 5.5 pg ml^{-1}). Further research demonstrating the effect of specific loading upon acute neuromuscular and endocrine response was presented by Schumann et al. (2013), which although not involving rugby players and combining training modalities that would not typically be seen in elite rugby settings, provides further knowledge to the area of training session recovery. The research by Schumann et al. (2013), which compared the effect of combined strength and endurance training sessions with strength and endurance training sessions prescribed individually, noted that that endocrine function (decreased concentrations of serum testosterone), remained elevated after 48 hours of recovery post the combined strength and endurance sessions. These findings therefore illustrate the differing responses created by specific training sessions.

Other research of interest for practitioners in the elite setting, is that by Beaven, Gill, and Cook (2008), who demonstrated the influence of gym based sessions upon resultant fatigue and identified large individual differences in testosterone responses to four differing resistance exercise protocols. Their recommendation was the monitoring of hormonal responses to gym based exercise stimuli. When considering the evidence outlined above, which illustrates the effect of specific training sessions upon rates of recovery, one could therefore argue that the likely restoration of performance rates, following a combination of field and gym sessions, would result in a lengthened recovery period post-session in comparison to a gym based

session alone. Additionally, when considering the view of Cook, Kilduff, Crewther, et al. (2014) that resistance training sessions provide a welcome distraction for players from rugby training, the role of such gym based sessions alongside field sessions, are further supported. When combining these views of Cook, Kilduff, Crewther, et al. (2014), with research showing increased testosterone levels as a result of gym based sessions (Kraemer & Ratamess, 2005), the need for careful session prescription is evident. Another interesting potential area of future investigation, would be a recommendation for the use of midweek measurement of testosterone and cortisol ratio as a predictor of readiness leading into completion as presented by Gaviglio and Cook (2014), who noted that the pertaining testosterone and cortisol ratio was significantly lower ($p < 0.01$) before a win than a loss. More recent support for the use of cortisol measurement in the days preceding rugby union matches was illustrated by (Crewther, Potts, Kilduff, Drawer, & Cook, 2017), who noted a large midweek rise in cortisol prior to matches which were won, whereas cortisol decreased before matches that were lost. However, when considering the limitations associated with hormonal testing outlined in Chapter 2.4.4.2 the reliability and applicability of such measures into elite settings is questionable.

Additional important aspects to consider within the recovery adaptation process of rugby players post-match and training is firstly that fitter athletes are expected to recover more quickly, as reported by Johnston, Gabbett, Jenkins, and Hulin (2015) when assessing Yo-Yo intermittent recovery test (level 1) (Yo-Yo IR1), 3RM back squat and 3RM bench press. When assessing the influence of physical qualities on post-match fatigue in rugby players Johnston et al. (2015) noted that stronger, fitter players recovered more quickly than weaker players even if physical match loads were greater. Johnston et al. (2015) concluded that post-match fatigue was reduced in players with well-developed high intensity running ability and lower body strength. Results showed larger reductions in CMJ power in the low Yo-Yo group at both 24 (ES = -1.83), and 48 hours post-match (ES = -1.33). This notion that fitter athletes recover more quickly in team sport settings is supported by Hunkin, Fahrner, and Gastin (2014), who noted smaller disturbances in CK values prior to Australian rules football games along with smaller metabolic disturbances following high intensity activity. In a review of neuromuscular function post-EIMD, muscular strength has also been noted to influence the fatigue response of players post team sport involvement, with greater strength augmenting the SSC, thereby placing less stress on the contractile properties of the muscle (Byrne, Twist, & Eston, 2004). Although collision situations in team sports such as rugby are the main contributor to muscle damage (Johnston, Gabbett, Seibold, & Jenkins, 2014; Twist et al., 2012), enhancing the ability of muscles to manage SSC activities may moderate the effects of this muscle damage and therefore hasten the recovery process.

2.3.9 What is readiness?

Throughout this thesis the term 'readiness' is used to describe athlete preparedness and overall state of fatigue, which may affect their ability to perform a task. Within this research the concept of readiness concerns a more holistic view of rugby players' preparedness to complete training tasks and optimal game day performance, with the aforementioned fatigue, restoration of performance and NMF, being important aspects in assessing overall readiness. A definition of readiness is "the willingness or a state of being prepared for something" (Cambridge Dictionary Online, 2015) and the term "readiness to train" has been used in recent research (Cook, Kilduff, Crewther, et al., 2014; Mann, Lamberts, & Lambert, 2014; Taylor, Cronin, Gill, Chapman, & Sheppard, 2010) when discussing a variety of sports science and strength and conditioning

topics. Readiness in pursuit of optimal athletic performance should also concern the state of being prepared, yet in sport it concerns the ability to complete the athletic task in question. The importance of player readiness within both preparation (pre-season) and competition (in-season) periods is paramount. In-season assessment of rugby players' readiness concerns their potential to perform their role within game situations to their optimal ability, while in pre-season periods assessing player readiness is key to enabling optimal athletic development during these periods of intense training. The link between readiness and fatigue is evident when considering the research in Chapter 2.3. The factors that affect fatigue and subsequent performance in relation to readiness are critiqued in more detail below.

2.3.10 Summary

Fatigue is more likely when playing exposure accumulates without sufficient rest (minutes and number of games played and training volume) and as games cannot be rescheduled due to the presence of fatigue the training load needs to be managed. As is evident from the research reviewed above, many tests of performance exist in the elite field, yet the applicability of the measures for the sport in question is a key consideration when aiming to maximise performance. Much of recent performance testing has focused upon attempting to quantify fatigue and the resultant readiness for competition. The need for such testing within team sport settings such as elite rugby union is paramount when considering the match demands outlined in previous chapters in addition to the large number of games played on a weekly basis over a nine-month period. Fatigue is expected post rugby union match play and the ability for practitioners to make informed decisions based upon fatigue testing using performance measures is therefore the goal. As noted above, the mechanisms of fatigue are wide ranging and the specific tests that examine all levels of fatigue (chronic and acute) that may be experienced post rugby union match play need to be quantified within the performance tests administered. If meaningful levels of fatigue are detected, practitioners need to be careful in selecting prescribed training sessions between games, as the evidence above illustrates the affect that some forms of training may have upon subsequent rates of recovery, due to the potential fatigue created. Reliable and applicable monitoring tools, which assess rugby player readiness throughout a playing season, combined with appropriate training prescription will aid in enhancing the likelihood of optimal performance.

2.4 Methods of Assessing Fatigue, Recovery and Readiness

Readiness and its importance within exercise prescription in the days post-competition is discussed in more detail later (Chapter 2.6), yet the understanding of the term readiness needs clarity by evaluating many of the methods of assessing recovery and restoration detailed below. Within this research readiness is considered to be the ability to perform without impaired performance, and not simply full recovery from muscle damage, with the terms readiness, recovery and restoration of performance used interchangeably. In their review of current methods for monitoring fatigue in high performance sport Taylor, Chapman, Cronin, Newton, and Gill (2012) noted that 61% of the respondents in their research reported using jump tests, submaximal tests or sport specific tests to assess readiness, varying in frequency from weekly, to monthly or daily. Practitioners in the elite team sport settings are commonly presented with the question of how fatigued their athletes are and how they can accurately quantify fatigue (Chiu & Barnes, 2003; Twist & Highton, 2013). Many of the performance measures used to diagnose fatigue to date have used “time to fatigue” tests, with exercise performed at a fixed intensity being used as a tool against which to compare substrate kinetics and hormonal response. However, as critiqued below, many of time to fatigue tests involve maximal efforts, using performance tests that are not sport specific, therefore creating unwanted additional fatigue and questionable results.

Due to the limitations associated with maximal testing mentioned above; requirement for non-invasive monitoring tools for assessing recovery status (restoration of NMF) in athletes are needed, with recovery markers advised to be sensitive to daily variability in training load (Meeusen, Duclos, et al., 2006). The monitoring tools and practices chosen will often be dependent upon the sport in question, with many monitoring tools being utilised within rugby alongside each other to represent best the fatigue and readiness of players. The following sections detail the methods commonly used for monitoring fatigue and readiness within high performance training environments, many of which are represented in Table 2.13. A major point of consideration for practitioners is that of reliability where it is seen to vary across testing method used. In addition, there are some testing methods, such as perceptual methods of fatigue assessment, whose reliability is difficult to test. Hopkins (2000) noted the reliability of performance measurement, such as jump testing, occurred when there is neither marked systematic nor random variation in data across different testing apparatus. The reliability of performance tests would therefore be more apparent if the reproducibility of the measure of performance was consistent when administered on several occasions.

Table 2.13: An overview of performance measures utilised in rugby

Tool	Areas measured	Reliability (ICC/SDD/SWC)	Advantages	Disadvantages	Minimum recommendation for use
Questionnaire (McLean, 2010; Johnston, 2013; West 2014)	Muscle soreness Fatigue Mood Appetite Sleep	Unknown Perceived measures validity questioned	Cheap and easy to administer Reported to be sensitive to changes in performance in team sports	Subjective and can be manipulated by player performance	Record daily as variation may be small
Blood markers (Elloumi, 2003; Maso, 2004; Mashiko, 2004; Crewther, 2009; Cunniffe, 2010; Johnston, 2013; West 2014)	Creatine kinase Testosterone:Cortisol	Varied (West, 2014; CV <10%) (Elloumi, 2003; CV <10.9%) (Maso, 2004; CV <10.5%) (Crewther, 2009; CV <10.5%)	Helps develop an understanding of the physical fatigue mechanism via the vast number of markers	Costly and invasive meaning difficult to implement into training programs	Unrealistic to implement daily/weekly so investigation When other parameters show reductions often the best option
Neuromuscular performance (McLellan, 2012; McLean, 2010; Duffield 2012; Johnston, 2013; Cadore, 2013; West 2014)	CMJ MVC Single Joint – Knee Extensor Peak power	Good (Johnston, 2013; ICC 0.98 PP, 0.97 PF) (Cadore, 2013; ICC 0.94 RFD)	An indirect marker of fatigue which can be implemented into training program	Difficult to identify match specific fatigue	Record weekly on the same day post-match applying intervention when dropping below baseline values
Performance tests (Coutts, 2007a; Lovell, 2013)	Running velocity RPE & training loads	Good (Coutts, 2007a; ICC 0.93 MSFT)	Helps assess match fatigue and provides more subjective measures	Time consuming and often adds more fatigue	Often best used during pre-season periods or when returning from injury – limited data on this method
Functional state (Edmonds, 2013; Morales, 2014; Buchheit, 2010)	Heart rate HRV	Unknown (Morales, 2014; ICC >0.81 HRV) (Buchheit, 2010; CV <10.5%)	Provides information on functional state without fatigue	Expensive to implement and few studies confirming reliability	Three assessments a week have been recommended – implementing this to a whole team sport playing squad is unrealistic (Plews, 2014)

2.4.1 Maximal and sub-maximal performance tests

Sub-maximal tests reported to be used by practitioners include; the heart rate interval monitoring system (HIMS), heart rate recovery (HRR) testing and Yo-Yo IR, with sub-maximal tests noted by Taylor et al. (2012) to account for 14% of performance tests utilised. Maximal tests in contrast to sub-maximal tests include; Wingate cycling tests, maximal strength testing and jump testing. Such maximal tests include any activity where the participant is asked to engage in maximal effort. While the design of sub-maximal and maximal performances tests specific to the sport in question have been developed, the specificity of the movements involved can be questioned (Coutts, Reaburn, Piva, & Murphy, 2007; Coutts, Reaburn, Piva, & Rowsell, 2007; Rowsell, Coutts, Reaburn, & Hill-Haas, 2009). Considering fatigue, which was described in Chapter 2.3.2, as being the inability to maintain force or power output at the required level, maximal performance tests are perhaps the most appropriate measure of in this case.

Maximal performance tests have been shown to be a definitive marker for NFOR in team sport athletes (Coutts, Reaburn, Piva, & Rowsell, 2007; Krusturup et al., 2010). Additional support for maximal decrement tests is present in the findings of Coutts, Reaburn, Piva, and Rowsell (2007) where MSFT performance and VO_{2max} testing decreased following six weeks of intensive training in rugby league players. Further support for maximal performance tests was noted by Krusturup et al. (2010) within female soccer research, which showed significant inverse correlations between Yo-Yo IE2 test performance and fatigue index during the repeated sprint test both at rest ($r = 0.76$, $p < 0.05$) and after the game ($r = 0.66$, $p < 0.05$). However, maximal performance testing should be administered with caution as it can create additional fatigue within the athlete.

Limitations exist for sport specific running tests. Firstly, fatigue as a result of the testing needs to be considered and secondly, a lack of opportunity to add testing to weekly scheduled training programs may hamper implementation. Additional lack of support for maximal testing, outlined by Darrall-Jones, Jones, Till, and Roe (2015), demonstrated that sprint tests in elite rugby players over 10 m, 20 m and 30 m were incapable of detecting smallest worthwhile change in performance. Despite a sub-maximal cycling tests (using HIMS or HRR) not being as specific to a team sport setting such as rugby as a running based test would be, it can be argued that it is more suitable to the competition and training environment that exists within teams playing on a weekly basis. Considering the multifaceted nature of fatigue research and the many consequences of fatigue, maximal performance tests are perhaps the most likely to replicate the athletes event, yet the logistical issues and added fatigue surrounding maximal testing within competition periods make this form of testing limited in value. Similarly, when testing within a sport such as rugby, where running movements are required, running specific maximal testing would likely be the tool of choice for many practitioners to assess fatigue in rugby. However, running specific maximal testing are perhaps not the most logistically viable testing option due to the additional fatigue these tests can add and the time needed to conduct them.

As a result of maximal performance tests producing data that represents a more comprehensive description of NMF, performance tests incorporating maximal testing are perhaps the most valid for use in elite settings. Questionable validity, however, exists within sub-maximal performance tests (Artero et al., 2012; Murphy & Wilson, 1996; Noonan & Dean, 2000), with future research recommended for use in elite sport settings (Rampinini et al., 2007). Due to the questionable validity associated with maximal tests and the added fatigue that maximal tests can create, the use of Wingate cycling tests and maximal strength testing were excluded from use in future discussion within this research. Maximal jump tests were, however, considered a practical tool for use within the elite rugby setting in question, as they can be easily implemented into training programs and add no additional unwanted fatigue. The most commonly used forms of sub-maximal and maximal performance tests are reviewed below, to help explain their inclusion or exclusion within future discussion within this research. It is, however, important for practitioners to note that maximal jump testing and maximal running testing, for example, are both very different in response to the physical dose applied. Whereas a maximal jump test may involve high muscular exertion, other maximal test varieties may involve high aerobic or anaerobic exertions, which will result in a differing physiological cost following their implementation.

2.4.1.1 Maximal strength testing

The most common maximal performance measures used in past research within team sports are maximal strength assessments. Many maximal strength assessments have been used to monitor progress throughout training cycles (Argus et al., 2009; Beaven, Cook, et al., 2008; Comyns et al., 2010; Harris et al., 2008), yet few have focused upon maximal strength testing to measure fatigue (Haff et al., 1997). Much of the modern research using strength training to assess performance has rarely used standard measures of strength training, which, utilise percentage of one-rep maximum calculations (%1RM) and has instead used maximal isometric voluntary contraction (MVIC). The reason MVIC has been preferred to %1RM testing is that it determines the volitional force-generating capacity of a muscle under relatively standard conditions, whereas strength training does not. Recent support for the use of MVC for assessing EIMD was presented by Damas, Nosaka, Libardi, Chen, and Ugrinowitsch (2016) who noted MVC to be the best EIMD indirect marker, when researching retrospectively across 286 athletes. Additionally, traditional strength testing is fatiguing in nature while other maximal testing such as CMJ and MVIC are not and are therefore considered to be more applicable for use in elite team sport settings. MVIC assessment enables generation of a force-time curve, which can identify multiple markers of neuromuscular performance; yet contrasting support for the use of maximal strength assessment exists. Cairns et al. (2005) noted maximal strength as an invalid assessment for fatigue, due to the extent to which they replicate the nature of sports activities in question. Research by Verdijk, van Loon, Meijer, and Savelberg (2009), however, noted that 1RM strength tests represents a valid means to assess leg strength in humans, with recommendations for using 1RM testing to assess changes in strength following an exercise intervention. The relevance of assessments of strength is that they could be applied to the fatigue testing proposed in this research.

As previously discussed, reliability of performance tests are of paramount importance for practitioners in order to ensure that the data collected is accurate and valid. Data within maximal strength testing have presented contrasting reliability, which was further supported by Soares-Caldeira et al. (2009) when assessing 1RM tests in adult women. Comfort, Jones, McMahon, and Newton (2015), by contrast, noted high test/retest reliability during the isometric mid-thigh pull (IMTP), with >1.3% change in peak isometric force, > 10.3% in mRFD, > 5.3% in impulse at 100 ms, > 4.4% in impulse at 200 ms, and > 7.1% in impulse at 300 ms being considered meaningful, irrespective of posture adopted. Further support for the reliability (ICC > 0.90) of using isometric testing was noted by Bazyler, Beckham, and Sato (2015) with isometric squat noted as providing a strong indication of changes in strength and explosiveness during training. Recent research by Haff, Ruben, Lider, Twine, and Cormie (2015) presents an important consideration for practitioners, as the method used to assess RFD during an isometric mid-thigh clean pull (IMTCP) impacts on the reliability of the measure. Haff et al. (2015) did, however, acknowledge the reliability of the IMTCP (ICC 0.95, CV < 4%), thereby further supporting the use of isometric testing. Lastly an isometric posterior lower limb muscle test was reported by McCall et al. (2015) to be a reliable and sensitive measure to track match-induced fatigue in professional soccer players. This three second isometric contraction of the lower limb showed high reliability for dominant leg at 90° (CV = 4.3%, ICC = 0.95, ES = 0.15), non-dominant leg at 90° (CV = 5.4%, ICC = 0.95, ES = 0.14) and was sensitive enough to detect reductions in force for dominant leg at 90° ($p = 0.0006$, $ES > 1$) that could present valuable insights for future recovery practices in elite soccer.

Limited research exists regarding the magnitude of change of strength measures that signify fatigue, and as discussed previously, maximal strength testing is likely to induce fatigue and therefore should not regularly be implemented into elite settings. Recent research by Comfort and McMahon (2015) does, however, demonstrate high reliability for maximal strength implementation of the back squat (ICC = 0.994) and power clean (ICC = 0.997) performance in experienced lifters. From the research by Comfort and McMahon (2015) practitioners were advised to look for a change of > 5% in order to identify meaningful change in maximal strength back squat and power clean. Additional support for resistance training to measure readiness was, however, presented by Crewther et al. (2013) when assessing salivary testosterone and cortisol responses to resistance training workouts. They claimed that free testosterone responses to a midweek workout might provide an early sign of team readiness to compete. Despite support for the reliability of maximal strength testing to assess fatigue in rugby league players, contrasting evidence exists in research by Coutts, Reaburn, Piva, and Murphy (2007), who report minimal reductions in 3RM bench press and squat assessment during overreaching periods. This minimal change during overreaching periods, therefore, demonstrates a likely lack of support for the use of strength testing for assessing fatigue. Many of the other methods of performance testing critiqued within Chapter 2.4.1.2 and 2.4.4 (jump testing and biochemical testing) provide more detail and specific values that signify meaningful change, with rate of force development and variability in hormonal profile of rugby players in the days post-match providing more objective values than those reported for maximal strength.

In a review of models used to evaluate NMF, Cairns et al. (2005) discussed the use of mechanical fatigue measures using MVIC, such as isokinetic dynamometer exercises and dynamic knee extension, with research in rugby specifically conducted by Crewther et al. (2009) illustrating significant relationships between neuromuscular performance and hormone secretion patterns in elite rugby union. Within the research by Crewther et al. (2009) concentric mean and peak power during a 70-kg squat jump mean power ($r = 0.41$, $p < 0.05$), 50-kg bench press throw PP ($r = 0.41$, $p = 0.05$), and estimated %1RM strength for a box squat and bench press were positively correlated with salivary testosterone and cortisol concentrations. Another study using strength testing (3RM bench press and squat) to measure performance and readiness was that of Cook, Kilduff, Crewther, et al. (2014) who noted testosterone concentrations to be offset by morning training, thereby recommending morning based strength testing to improve afternoon performance in rugby union. Additionally, Johnston et al. (2013) supported the notion that upper body power is also a good indicator of NMF post rugby match and that upper body PP appears to be a suitable measure for the specific force related exertion involved in tackling. It is, however, important to note that time-course and mechanisms of fatigue of the upper body differ to that of velocity based lower body power movements.

From the research within this section it is clear that questionable validity and reliability exist within both maximal strength testing and MVIC testing. Due to these validity and reliability issues, along with the lack of access to facilities and manpower needed on a regular basis for both maximal strength and MVIC testing, these performance measures are excluded from future use within this research. Additionally, the equipment required for testing isometric contractions (isokinetic dynamometers) are large in size and therefore cumbersome and expensive to use. Added to the fact that additional fatigue can be created as a result of both these forms of performance testing it is clear rationale to exclude their use within this research.

2.4.1.2 Maximal Jump testing

2.4.1.2.1 Common uses of jump testing

An individual's ability to generate force quickly is a key performance measurement for athletes competing in many team sports, hence jump tests have often been utilised to monitor power (Markovic et al., 2004). With the goal of assessing lower limb power, many jump tests including vertical jump have been developed. The vertical jump has, however, been reported to represent an inaccurate measure of explosive lower limb power due to the more complex nature of leg/arm coordination (Leard et al., 2007; Markovic et al., 2004; Young, MacDonald, Heggen, & Fitzpatrick, 1997). Jump tests commonly used in the applied setting include CMJ and squat jump (SJ). CMJ involves the use of the stretch shortening cycle, whereby subjects perform a downward movement from an erect standing position until they feel comfortable and then jump for height in an upward motion. SJ is a pure measurement of concentric power, whereby the subject is instructed to squat to 90°, then hold for three seconds at the bottom of squat and jump on a command.

The jump modalities mentioned above have come under scrutiny because of the technique many subjects used along with inconsistent testing protocol (Markovic et al., 2004). Testing irregularities such as the subject's ability to swing their arms for greater height and the effect of pre-stretching meant that recent jump testing has focused solely on the SJ and CMJ. Lees, Vanrenterghem, and De Clercq (2006) concluded that arm swing contributes to jump performance by aiding the storing and release of energy from muscles and tendons around the ankle, knee and hip and by initiating a pull force at the shoulder joint, thus increasing jump height by 10% or more (Lees, Vanrenterghem, & De Clercq, 2004). Additionally, this use of arms in vertical jump performance has been reported to provide 10% mean increase in take-off velocity (Carlock et al., 2004; Harman, Rosenstein, Frykman, & Rosenstein, 1990). Therefore the use or exclusion of arm movement needs to be standardised during such assessments in order to ensure that they are comparable. Due to the above inaccuracies detailed regarding vertical jumps, they have been excluded as a reliable test for jump performance from more recent research (Acero, Sanchez, & Fernandez-del-Olmo, 2012).

2.4.1.2.2 Jump testing tools

In addition to jump testing protocols being scrutinised for inaccuracies, specific jump and power testing tools have also come under criticism. Numerous instruments measuring jump height and contact time, utilising different technologies and calculations, have provided varying results (Markovic et al., 2004). Force plates have been considered to be the "gold standard" for the measurement of jump tests, having been reported to provide excellent measurement accuracy for estimation of power via forward dynamics, calculated by the force applied to the jumping surface (Walsh, Ford, Bangen, Myer, & Hewett, 2006). Jump instruments such as optical measuring systems, that solely assess flight time and do not determine jump height from the impulse-momentum relationship, as used by Domire and Challis (2007) are at risk of inaccuracy, as subjects can alter jump technique, such as a flexed foot on landing to increase flight time. By contrast, when using force plate assessment maximal vertical velocity of the centre of mass at take-off provides a more accurate measure of jump height, by using a forward dynamics approach. Cormack, Newton, McGuigan, and Cormie (2008) highlighted the importance of analysing the flight time to contraction time ratio as a measure sensitive to fatigue, with the time from initiation of the counter movement until the subject leaves the jumping surface being key. It is, however, important for practitioners to note that despite the

research by Cormack, Newton, McGuigan, and Cormie (2008) reporting flight time to contraction time as the measure of jump performance, the methodology used actually assesses only the initial movement when utilising velocity of the centre of mass jump testing protocol. Movement may have also occurred in the upper body prior to contraction of the lower body during velocity of centre of mass assessment using the protocol by Cormack, Newton, McGuigan, and Cormie (2008), and one cannot therefore assume that the initial movement reported is contraction time. Also of note for practitioners is that, despite the research by Cormack, Newton, McGuigan, and Cormie (2008) not stating the sampling frequency used for the force plate assessment; typical *Ballistic Measurement Systems* use a frequency of 40 ms. As a result, it could be argued that this default sampling frequency option may prove inaccurate, when compared against research which involved a different sampling frequency. Practitioners are therefore advised to note both the thresholds set for the onset of movement and the calculation used for flight time, as this may have an effect upon the resultant measurement variables collected.

Force plates have been shown to possess excellent reliability as performance measures for both jumping and landing tasks and strength assessment (Cormack, Newton, McGuigan, & Doyle, 2008; Cormie, McBride, & McCaulley, 2007; Walsh et al., 2006), while use of saliva to assess hormonal response post rugby match is commonplace (Beaven, Cook, et al., 2008; Crewther et al., 2013; Elloumi, Maso, Michaux, et al., 2003; Elloumi, Maso, Robert, et al., 2003; Maso, Lac, Filaire, Michaux, & Robert, 2004; West et al., 2014). Force plates use the impulse-momentum relationship to determine velocity, which calculates power through the forward dynamics approach (Cormie et al., 2007). Previous research has utilised the flight time calculation via the height of rise of centre of mass (French et al., 2004; McBride, Triplett-McBride, Davie, & Newton, 1999, 2002). The vertical take-off velocity of the centre of mass is calculated, whereby acceleration (a) is determined by dividing vertical ground reaction forces (F) by the mass of the system (SM) at each time point:

$$a = F/SM$$

With jump height from velocity of centre of mass calculated via the following equation:

$$JH = (v^2)/(2 \times 9.81)$$

$$v = \text{displacement/time}$$

This method of forward dynamics calculation has been regularly used to assess bodyweight jumps in previous research (French et al., 2004). However, the main disadvantages associated with force plates are that they are expensive to use and often impractical in field-testing scenarios (Casamichana et al., 2013). Additionally, methods of assessing power output via kinetic methods such as the force plate have been questioned (Cormie et al., 2007), with force plate methodology typically used to compare performance of bodyweight jumps, rather than to measure the influence of loads upon power output. During Olympic lifting movements, for example, the barbell moves at a differing rate to that of the participants centre of mass (COM), as the barbell starts below the lifter's COM and finishes above their COM meaning the power applied will differ. On summary the advantages of force plates outweigh the disadvantages mainly due to the vast amount of data that force plates can collect including such parameters as PRFD and impulse (McLellan & Lovell, 2012; McLellan et al., 2011a, 2011b; McLellan, Lovell, & Gass, 2011c; McLellan et al., 2011d).

Recently, contact mats and optical measuring systems have become commonplace for field based assessments (Bosquet, Berryman, & Dupuy, 2009). CMJ and SJ performed on a contact mat were deemed reliable at estimating anaerobic power in a study by Moir, Button, Glaister, and Stone (2004). Contact mats were also considered practical for use in laboratory and field settings, for squat jump and CMJ (Markovic et al., 2004). This was mainly due to the nature of the testing protocol in the field and the ability for data to be produced relating not just to jump height, but also to various other parameters to assess power (Casartelli, Muller, & Maffiuletti, 2010). Bosco, Luhtanen, and Komi (1983) were the first to derive jump height from flight time via a contact mat, with infrared optical device now replacing contact mats to measure flight time. However, due to error in time keeping by subjects taking off and landing in different locations, this method of calculating jump height has been questioned (Garcia-Lopez et al., 2005). The main criticism, that contact mats cause inaccuracies, has been based on the fact that the subject's feet are not directly in contact with the specific sport surface in question, with the result that athlete surface interaction varies (Markovic et al., 2004). Although this inability to test on specific surface is also seen in force plates, the advantages of force plates outlined above mean that this is not considered a major concern.

If methodological protocol is standardised throughout jump testing, the effect of differing surfaces and other dependent variables such as technique used will be minimised. Accuracy of data collected on contact mats was researched and evidence for its use questioned by Klavara (2000), who found that subjects recorded higher jump scores with a contact mat than a jump and reach style test as used in NFL combine testing (Kuzmits & Adams, 2008). In recent research (McMahon, Jones, & Comfort, 2015) a commonly used contact mat (*JustJump*) was compared against a force plate, with suggested use of a corrective equation when using a *JustJump* system, despite ICC demonstrating excellent within-session reliability of CMJ height ($ICC = 0.96$, $p < 0.001$). Jump and reach tests have also come under scrutiny as the techniques used by participants, as a subject-performing jump and reach tests can use the wall as an aid to extend jump height. Harman (1990) reported that jumping and touching a wall during a vertical jump is more restrictive than jumping straight up and down, hence their study found jump height to be 5.3 cm greater when using a total body centre of mass displacement, compared to the jump and reach test. Additionally, it is assumed that participants on a jump and reach test will mark the wall or displace a marking vane at the peak of their jump. As reported by Klavara (2000) this is often not the case, therefore influencing results collected.

Early research, assessing the validity and reliability of methods for testing vertical jump performance are being questioned due to methodological considerations (Hatze, 1998). In the research by Hatze (1998) the methodological limitations noted include; invalid assumptions regarding performance calculations and the jumping technique utilised. This is despite the use of force plate methods supported by research (Walsh et al., 2006). Jump mats, for example, use flight time as the calculation of performance, yet this calculation is an approximation, as flight time is no direct measurement of force. By contrast, force plates give direct measurement of force based upon the forward dynamics discussed earlier. If the calculations used to assess performance incorporate displacement time data involving direct measure of velocity, it is important for practitioners to acknowledge that this measure is an approximation of force, therefore its accuracy should be questioned. This view was supported by Hatze (1998) who noted that the validity and reliability of the jumping ergometer method for evaluating certain aspects of athletic performance are highly questionable, due to the methods of calculation

identified above. More recent research has, however, shown jump testing that uses modern methods as reliable (Markovic et al., 2004). Technological development of contact platforms and mobile devices (*My Jump*) has been reported to produce reliable intra and inter-session data during drop jump, CMJ and SJ movements (Gallardo-Fuentes et al., 2016).

2.4.1.2.3 Jump testing – kinetic and outcome based measures

When considering that PRFD is noted by McLellan et al. (2011d) to be a primary contributor to jump performance during CMJ, the need for validity of this measure for testing performance is needed. Despite data showing a relationship between RFD and CMJ height being limited, eccentric movement is generally considered to be a fundamental component of the SSC and is, therefore, important for consideration when assessing CMJ performance of team sport athletes such as rugby players. Similarly, the ability to develop force rapidly is a prerequisite for explosive strength, yet a scarcity of knowledge regarding RFD correlations to vertical jump exists. RFD relates to short components of the SSC and are characterised by small angular displacement (100 to 250 ms) of the ankle, knee and hip joints during CMJ. The eccentric phase consists of the point in the downward movement, where the force being exerted into the force plate exceeds body weight until the point of zero velocity at the lowest point of the countermovement. Eccentric RFD concerns the peak power exerted during the eccentric phase of the CMJ and is measured in $N.s^{-1}$, with the ability to handle the maximal eccentric force in the minimal time possible being a typical indicator of explosive strength. Research showing relationships between eccentric RFD and CMJ performance are contrasting, with McLellan et al. (2011d) assessing the RFD on vertical jump performance on a force plate and noting poor retest reliability (CV 16.3%) in twenty-three physically active men. McLellan et al. (2011d) did, however, note that significant correlations between maximum RFD and jump height could only explain 46% of the variance noted in jump height and that the other variance is likely to be due to inexperience of the subjects in question. Research by Ebben, Flanagan, and Jensen (2007) noted no correlation between RFD and CMJ ($r = 0.19$, $p = 0.22$) and therefore questioned the usefulness of RFD for assessing CMJ performance. As was argued by Ebben et al. (2007) and noted within previous research (Haff et al., 1997), the use of RFD may be more suited to high load activities such as mid-thigh clean pulls.

The availability of reliability statistics for eccentric RFD is limited, with Moir, Garcia, and Dwyer (2009) reporting RFD values (CV 17-21%), yet it must be noted that the values presented by Moir et al. (2009) are from non-elite men and women. Within the research by McLellan et al. (2011d) a significant relationship existed between vertical jump displacement (VJD) and PRFD for the CMJ ($r = 0.68$; $p = 0.001$). In contrast, a non-significant relationship ($r = 0.65 - 0.74$) between RFD and vertical jump performance was noted by Hopkins, Schabort, and Hawley (2012), yet the lack of statistical significance within that research is likely to be explained by the poor statistical power ($n = 8$). Additionally, the research of McLellan et al. (2011d) showed that eccentric RFD displayed low reliability, however, an important point for consideration when comparing the results of McLellan et al. (2011d) to other research is the differing testing apparatus used. Within the research by McLellan et al. (2011d) a sampling frequency of 1000 Hz and a cut off frequency of 17 Hz was used, with this methodology likely to differ across studies.

Perhaps most interesting within future kinetic measures research, is the findings of Gathercole, Sporer, Stellingwerff, and Sleivert (2015a), who, when assessing the reliability of CMJ, noted that the variables with a CV > 5% related to the eccentric phase of the CMJ, while variables with

CV < 5% included those that relate to the concentric outcome of the jump performance. Gathercole, Sporer, Stellingwerff, et al. (2015a) therefore argued that assessment of CMJ performance should include both variables that assess changes in outcome and variables that determine the jump strategy employed by the subject, for there to be a more informed consideration of the movement behaviour. In an analysis of male college-level team-sport athletes, Gathercole, Sporer, Stellingwerff, et al. (2015a) noted that most kinetic variables take longer to return towards baseline values at 72 hours post-exercise, when compared to CMJ output (typically concentric focused variables), with these views supported by Kennedy and Drake (2017b) in rugby players, comparing isometric strength and CMJ output variables. Gathercole, Sporer, Stellingwerff, et al. (2015a) therefore recommended that practitioners consider NMF by assessing changes in both output and/or movement economy. The research proposed below will assess players' ability to jump as high as possible, yet the kinetic measures that are often used within jump performance assessment need also to be considered. It could, however, be argued that in terms of restoring performance post rugby union match play, assessment of jump height is the most essential measure of performance, as this relates specifically to the players' ability to out jump their opponents and will therefore result in improved likelihood of team success. However, the role that kinetic measures play in the assessment of jump performance cannot be discounted and is therefore examined further in the experimental Chapter 5 below.

2.4.1.2.4 Jump performance to assess fatigue

In addition to using jump tests that measure power, velocity, force, contact time and rate of force development; recent research (Hamilton, 2009; Kennedy & Drake, 2017a; Kennedy & Drake, 2017b; Mooney et al., 2013; Roe et al., 2015; Taylor, 2012) has focused on utilising vertical jumps to assess neuromuscular fatigue, with effectiveness of CMJ confirmed by Gathercole, Sporer, Stellingwerff, et al. (2015a). Reliability of CMJ analysis to quantify acute NMF using a force plate was also confirmed by Gathercole, Sporer, Stellingwerff, et al. (2015a). CMJ variables exhibiting intraday ($n = 20$) and interday ($n = 21$) CVs of < 10% were reported when assessed at zero, 24 and 84 hours following a fatiguing high-intensity intermittent-exercise running protocol. Additionally, effect sizes were reported to range from trivial to moderate in eighteen CMJ variables at zero hours immediately post exercise fatigue, further confirming CMJ as a reliable measure for NMF. Follow-on research by Gathercole, Sporer, Stellingwerff, et al. (2015a) showed high repeatability and immediate and prolonged fatigue-induced changes detected by CMJ (CV = 3.0%), when compared to other jump measures (SJ = CV 3.5% and DJ = CV 4.8%) and 20 m sprint times. Research by Markovic et al. (2004) also confirmed reliability of CMJ with intraclass correlation coefficients (ICC) being 0.98, while within-subject CV in CMJ was 2.8%, which was reported as low compared to other vertical jumps such as SJ and horizontal jumps (standing long jump and standing triple jump).

Other recent research of interest includes that by Roe et al. (2015) which suggests that CMJ mean power, peak force or mean force can be used for assessing lower body neuromuscular function, due to both their acceptable reliability and (CV < 5%) and good sensitivity (CV < SWC). The meta-analysis of CMJ and its use for measuring NMF presented by Claudino et al. (2016) noted that the majority of studies have incorporated highest CMJ performance values in contrast to the use of average values. However, Claudino et al. (2016) reported that the average jump performance was more sensitive than highest jump performance when assessing fatigue and recommended its application in applied settings, as, statistically, researchers have a higher

probability (10-1) of finding the true jump performance when the average value is used instead of the highest value. Despite these recommendations for use of average jump measures, the high reliability within and between-session reported and the recent success using CMJ for assessing NMF, it can be concluded that CMJ tests appear to be a suitable athlete-monitoring method for NMF detection. Specifically in relation to rugby, further support for jump testing to measure fatigue was presented by Twist et al. (2012), who reported that jump tests provide the most appropriate indirect marker of tissue damage and reduction in muscle force generating capacity. Recent research in elite soccer settings by Russell et al. (2015) also reported that creatine kinase (34.3%) demonstrated greater between-match variability than jump testing measuring peak power output (9.9%).

Jump tests are considered excellent indicators of neuromuscular function for athletes, due to the stretch-reflex involving both eccentric and concentric actions, as seen in jumping and hopping actions within rugby. Jump tests have commonly been used, as jumps are a convenient exercise for assessing NMF that is easy to implement into a high performance sport setting, while providing great ecological validity. Eccentric muscle damage, as seen in rugby union match play, has been noted, with Harrison and Gaffney (2004) showing reductions in many jump testing movements post-match exposure. Recent studies within elite rugby league found that CMJ performance was impaired for up to 24 hours post-match, along with reports of 26% reduction in PRFD 24 hours post-match (McLellan et al., 2011b; Twist et al., 2012).

2.4.1.2.5 The relevance of jump testing in elite performance settings

Twist et al. (2012) reported an inverse relationship between contacts and impaired CMJ flight time, indicating that players that are involved in more contacts experience more loading on the lower limbs musculature. This damage to lower limb muscles from contact situations can be attributed not only to the number of contacts, but also the to the large accelerations and decelerations leading into the contact situation. While most studies assessing neuromuscular recovery have utilised one CMJ repetition, Cormack, Newton, McGuigan, and Cormie (2008) used five continuous CMJ measuring flight time. Singular CMJ flight time has been seen to show more substantial reductions in performance compared to five repeated CMJ, suggesting that it is less able to distinguish between levels of neuromuscular function, despite its reactive nature and SSC involvement. Additionally, in research assessing muscle damage on SSC function (Harrison & Gaffney, 2004), CMJ was seen to show reduced levels of decrement compared to SJ. The findings by Johnston et al. (2013) suggest that maximal strength assessments are less affected than peak power outputs, meaning CMJ flight time is perhaps more appropriate for measurement of muscle damage than isometric measurements such as isolated leg press. Johnston et al. (2013) also reported that CMJ height correlates with sprint performance over 5 m, 10 m and 30 m. Hamilton (2009) noted a significant decline ($p \geq 0.05$) in drop jump reactive strength index (DJ-RSI) for youth soccer players following match play. Despite CMJ assessing flight time receiving praise as a modality to assess NMF (Cormack, Newton, McGuigan, & Cormie, 2008; Cormack, Newton, McGuigan, & Doyle, 2008), Hamilton (2009) noted DJ-RSI as being an appropriate test for use in team sport settings.

In spite of CMJ being the most commonly used jump modality, criticism surrounding CMJ exists and in some research has been replaced by other forms of jumps (drop jumps and squat jumps) (Hamilton, 2009; Kamandulis et al., 2011). Criticism of jump testing as a performance measure for measuring fatigue has been illustrated by Krstrup et al. (2010), who noted that jump tests

had no impact upon the type of fatigue post female soccer game. However, it should be noted that there are noticeable differences between female soccer players and male rugby union players in terms of the number of impacts encountered in match situations and the associated trauma and muscle damage. Considering the findings by Gathercole, Sporer, Stellingwerff, et al. (2015a), that mean power, peak velocity, flight time, force at zero velocity and area under the force velocity trace showed changes greater than the CV in most individuals, CMJ use is further questioned. Impaired neuromuscular function, due to utilisation of the more specific SSC nature of drop jumps (DJ) and the relatively short contraction times involved in the movement, lead to more sensitive measures. The increased sensitivity associated with DJ (reactive strength index) is in part due to DJ's using both contact and flight time measures, which as Hamilton (2009, p. 4) concludes "any technical alterations that develop to facilitate improved force capabilities" that can be associated with other jump modalities. The high speed and power qualities associated with rugby union match play perhaps deem DJ to be a more accurate measure of an athlete's current functional state, compared to data from bilateral jumps such as CMJ.

CMJ has however previously been reported to measure fatigue accurately (Duffield et al., 2012), with reduced values of CMJ and maximal velocity contraction of the knee in an isometric test shown to correlate match playing time undertaken by players in rugby league. Additionally, CMJ assessing NMF has previously been reported to be reliable and valid using the FT:CT calculation (Argus, Gill, Keogh, et al., 2012; Argus et al., 2009; Baker, 2001c; Cormack, Newton, McGuigan, & Cormie, 2008; Cormack, Newton, McGuigan, & Doyle, 2008; Mooney et al., 2013). McLean et al. (2010) recommended weekly CMJ testing to analyse the results, along with psychometric values to assess neuromuscular readiness. Findings such as those from Duffield et al. (2012) illustrate that intermittent-sprint team sports such as rugby union result in post-match suppression of skeletal muscle force. In a study by Johnston et al. (2013), assessing cumulative fatigue throughout a period of three games, decrements in defensive performance seen in game three correlate with reduced CMJ values, suggesting that lower body power is a prerequisite for tackling ability. Similarly, in a recent study assessing an intensified fixture schedule in professional rugby league, cumulative NMF (Match 1 vs. Match 2 -2.3%; -Match 3 - 6.9%; Match 4 -2.9%) was noted (Twist, Highton, Daniels, Mill, & Close, 2017). Lastly, as previously stated, decrement in jump performance post-match situations has been reported in many studies (McLellan et al., 2011b; Twist & Sykes, 2011; Waldron et al., 2011), with decreased performance reported in a period of up to 24 hours. Importantly though, prolonged increase in muscle soreness has been reported to last for longer than jump performance decrement, lasting up to 48 hours in some studies (McLellan et al., 2011b; Twist & Sykes, 2011). It is believed that this perceived soreness has an impact upon players' sense of effort during training, in the immediate days post-match, thereby having implications upon the quality of training that can be performed during this period. Potentially, however, jump performance values could still be collated in order to assess player readiness.

From the research above it is evident that jump testing is a performance test that warrants consideration for use within future studies in this thesis. Jump testing is a relatively easy and inexpensive performance test to implement in elite settings, with the research above illustrating its reliability and validity for measuring performance and fatigue, especially when a standardised testing protocol is administered.

2.4.1.3 Maximal ergometer testing

Another form of maximal testing uses ergometers to assess readiness with one of the most widely used anaerobic tests being the Anaerobic Cycling Wingate Test, where participants pedal maximally against a constant resistance proportionate to body mass. Wingate tests have been shown to provide reliable measures of peak power, mean power and fatigue (Bar-Or, Dotan, & Inbar, 1977) and when one considers that maximal cycling tests are not solely lower body power assessments, support for maximal cycling tests is unsurprising. Baker et al. (2002) concluded that a large contribution to the peak power output is made by the muscular skeletal components of the upper body, suggesting that a cycling ergometer test might be a whole body exercise. The anaerobic nature of Wingate tests and the research previously referred to, further support the use of maximal tests as a means for assessing rugby players. Anaerobic fatigue is a topic that has received a considerable amount of attention, with anaerobic and repeated sprint performance tests providing an index of anaerobic endurance. The percentage decline in power, relative to the peak value, represents the maximal capacity for ATP production via a combination of intramuscular phosphagen breakdown and glycolysis (McArdle, Katch, & Katch, 2005).

Maximal cycling efforts have been administered in rugby league to assess overreaching, with a decline in peak power during a ten second sprint after six weeks of intensive training reported (Coutts, Reaburn, Piva, & Murphy, 2007; Coutts, Reaburn, Piva, & Rowsell, 2007). This decreased performance was attributed to increased levels of muscle damage. An “off feet” test that does not involve “on feet” running mechanics is often deliberately chosen as a fatigue test, post-game in rugby union players, using the reliability of *WattBike* testing (Driller et al., 2014; Driller, Argus, & Shing, 2012). Currently unpublished data (Grainger, Ripley & Comfort, In Review), utilising 6” peak power testing on a *WattBike* in elite rugby union players, has recommended its use for assessing restoration of performance post-match situations. “Off feet” tests are considered to be a more sensitive and practical test to administer on rugby players post-match. The aforementioned blunt force trauma and high running volumes associated with rugby, along with the large body mass of players, mean that running in the days post-match would present the players at an increased injury risk. This increased injury risk would be accentuated by the nature of the maximal running tests; meaning that an “off feet” test would be more applicable. It could also be argued that an indoor test on a stationary bike would be more reproducible than a running test performed outside, which could be affected by weather and ground conditions, thereby creating inaccuracies.

2.4.2 Running specific performance tests for football codes

A reliable and robust measure of the performance of a rugby player for use as a tool for adjusting training schedules has long been required. Performance measures in most football code settings (soccer, rugby union and rugby league) seeking to replicate the movements of the sport generally, involve running specific activity which is challenging to implement and perhaps impossible to make accurate judgements upon. Typically maximal running tests have been used in rugby league (Coutts, Reaburn, Piva, & Murphy, 2007; Coutts, Reaburn, Piva, & Rowsell, 2007) with overreaching athletes identified via a MSFT following an intensified training period. Despite Coutts, Reaburn, Piva, and Murphy (2007) reporting on the state of overreaching, they noted that the most likely explanation for the decreased performance is increased muscle damage, via a decrease in the anabolic-catabolic balance, in addition to poor management of the training adaptation process. In another study examining performance tests for rugby (Austin,

Gabbett, & Jenkins, 2013) it was noted that repeated sprint ability tests alone may underestimate the repeated high intensity efforts seen in rugby match play and also the associated fatigue that this creates (Johnston & Gabbett, 2011). However, Austin et al. (2013) concluded that the findings from their repeated high intensity exercise performance test were adequately sensitive to detect training induced changes in rugby league and rugby union. Within the rugby league and rugby union research by Austin et al. (2013) varying reliability was noted, with ICC for total sprint time being moderate to high (0.82, 0.97, and 0.94) and CV low (4.2, 1.4, and 0.6%) for the backs, rugby league forwards, and rugby union forwards tests, respectively. Additionally, the reliability of running specific performance measures was questioned, when considering that sprint performance decrement scores were low, with ICC and CV of 0.78, 0.86, and 0.88 and 49.5, 48.2, and 35.8% for rugby league and rugby union backs, rugby league forwards, and rugby union forwards, respectively.

One could argue that these running specific performance tests and their associated training induced changes could present greater understanding as regards data upon which to assess player fatigue and overall readiness. Within “real world” elite rugby settings it is unrealistic to ask players to complete rugby specific testing measures. At times multiple players may be required to perform a contact situation drill that replicates elements of the game (to make the performance measurements as specific to the rugby tasks in question as possible), yet the drill is for the sole purpose of assessing one player’s fatigue or readiness. This further highlights the unrealistic expectations of such rugby specific performance tests “on feet”. Added to the impracticality of using specific rugby tests, the extra fatigue that these testing practices would induce make testing for readiness using rugby specific measures less appropriate for use in elite settings, where the days between games are short and an already busy training schedule makes the elite players compliance to such testing unlikely. Due to the impracticality of using rugby specific performance measures for assessing readiness, the monitoring of current functional capacity has focused upon indirect markers of performance such as alternative forms of maximal and submaximal testing and other relevant physiological and psychological assessments.

Cormack, Smith, Mooney, Young, and O'Brien (2014) assessed load per minute (LPM) via GPS data collection as a measure of exercise intensity. LPM was calculated via accumulated accelerations measured by tri-axial accelerometers, with Cormack, Monney, Morgan, and McGuigan (2013) concluding that, when considering LPM in conjunction with NMF data assessed via CMJ, it is apparent that LPM measures are acute to efficiency of movement performed, due to reduced neuromuscular function and would therefore be another performance measure upon which to judge player readiness. These GPS values such as LPM do, however, need to be validated for reliability, despite Mooney et al. (2013) showing similar GPS efficiency when assessing CMJ performance, Yo-Yo IR testing and subjective coaches’ voting. One could argue that jump testing could measure the SSC of athletes but would not provide a global measure of player fatigue in rugby union. It was argued that a player could perform a maximal jump despite being fatigued and therefore show no signs of decrement in their jump performance. Whereas a maximal effort performance measure test; such as MSFT or (Coutts, Reaburn, Piva, & Rowsell, 2007) Yo-Yo Intermittent Endurance Level 2 Test (Yo-Yo IE2) (Krustrup et al., 2010), would present more objective data upon the whole athlete, as regards neuromuscular function and cardiovascular readiness, it has been shown to be a definitive performance marker for NFOR in team sport athletes. However, many running specific tests,

although not maximal in nature, are harder to implement logistically than jump testing, for example, and can add to the training volume and subsequent fatigue of the athlete, meaning that it may not be the best performance measure for many sporting scenarios.

Sub-maximal running tests are commonly used within team sport settings (Buchheit et al., 2013; Cornforth, Robinson, Spence, & Jelinek, 2014), with heart rate derived measures used to assess readiness and general fatigue. Heart rate recovery (HRR) and heart rate variability (HRV) are two such performance measures and they can be used within sub-maximal exercise protocol as performance measures for fatigue. HRR and HRV are therefore considered for use within future studies within this research and are critiqued in more detail within Chapter 5.5.

2.4.3 Perceptual feelings of well-being

Performance tests provide a good indicator of an athlete's physical and psychological well-being; yet as mentioned previously, often add fatigue to participants and are therefore impractical for daily implementation. The goal of many sport practitioners is to provide a stimulus that improves prospective athletic performance, with many practitioners applying well-being (WB) questionnaires as a measure of finding out both how their players feel and how they are handling the training volume (Coutts, Wallace, & Slattery, 2007; Halson, Lancaster, Jeukendrup, & Gleeson, 2003). Support for the use of monitoring tools such as WB questionnaires is vast (Coutts, Wallace, et al., 2007; Elloumi, Maso, Michaux, et al., 2003; Johnston et al., 2013; Slattery, Wallace, Murphy, & Coutts, 2006), with coefficient variant for subjective mood state being 9-12% (Hooper & Mackinnon, 1995). Despite this, research into the effect of team success upon mood is still unclear (Gonzalez-Bono, Salvador, Serrano, & Ricarte, 1999). Mood disturbances, as assessed via questionnaire, have been reported to increase in a progressive manner as training load increases (Filaire et al., 2001; Saw, Main, & Gastin, 2016), while mood was noted to outlast hormonal responses post rugby union match (West et al., 2014). Subjective markers of fatigue include; the Profile of Mood States (POMS) questionnaire, the Total Quality Recovery Scale, the Passive and/or Active Recovery Scale and the Daily Analysis of Life Demands for athletes' questionnaire have been utilised in team sport studies of training effect and readiness (Filaire et al., 2001; Kentta & Hassinen, 1998; Shearer et al., 2016). Further support for WB questionnaires comes from Killen et al. (2010) who reported a trend towards higher injury rates and noticeable changes in psychological well-being. When considering that sensory psychological inhibition post-exercise is perhaps the main cause of fatigue during periods of high training volume (as illustrated in Chapter 2.3.2) further evidence for the use of WB measures, that can assess psychological readiness in the days post rugby game, are further emphasised.

As mentioned, support for the use of monitoring tools such as well-being questionnaires comes from Slattery et al. (2006). They claimed that the RESTQ-76 Sport questionnaire provided a practical tool for monitoring overreaching in triathletes. Recent research in team sport settings has also supported the importance of frequent monitoring of recovery and stress parameters to lower the risk of injuries in professional football, with the RESTQ-Sport questionnaire predicting injuries in the month after the assessment (Laux, Krumm, Diers, & Flor, 2015). Twist and Highton (2013) studied rugby league players' functional state in post-match situations and concluded that a multidimensional approach should be administered in order to test and manage fatigue, as an altered sense of effort was present, both when fatigued and during performing testing. When an impaired psychological state or mental fatigue is apparent

participants may down regulate their exercise capacity. This is therefore a point to consider for any future performance testing under a state of fatigue post-match. This notion was supported by Johnston et al. (2013) who noted that an increase in perceived muscle soreness might perhaps increase perceived effort, thereby reducing a rugby player's ability to perform optimally.

Subjective measures have been used to monitor fatigue in rugby, with previous research including self-report well-being questionnaires, showing reduced perception of readiness across a longitudinal period (Cresswell & Eklund, 2006). Evidence for the use of well-being questionnaires in rugby union was supported by Twist and Highton (2013) who found alterations in perceived fatigue and muscle soreness to outlast deductions in neuromuscular and biochemical markers. Fatigue and diminished performance throughout a rugby season is common, with previous research in rugby union (Argus, Gill, Keogh, et al., 2012) reporting a 3% decrease in lower body peak power during a competitive phase in rugby union, while a study assessing in-season strength and power characteristics in rugby league showed a decrease of 1% in lower body mean power (Baker, 2001b). Evidence for this resultant fatigue and reduced performance capacity have been represented by correlations between OT scores assessed via questionnaire and altered CK values. This evidence is apparent in the study by Alaphilippe et al. (2012) assessing biochemical markers over a longitudinal period in rugby union. In rugby specifically, perceptual fatigue (assessed via questionnaire) was reported to last up to four days post-match (Johnston et al., 2013). Twist and Highton (2013) reported a change of approximately 1 to 2 on a scale of 1 to 5 in muscle soreness, fatigue and attitude towards training in the 48 hours post rugby league game when assessing via a Likert scale. Nicholls, Backhouse, Polman, and McKenna (2009) noted that rugby union players described many self-report stressors as being "worse than normal" the day after a match, in comparison to days preceding and including match day.

Muscle soreness post-match has been effectively researched in previous rugby union research (Gill et al., 2006; Takarada, 2003) and was considered an appropriate measure upon which to assess recovery. When an impaired psychological state or mental fatigue is apparent, participants may down regulate their exercise capacity. As was discussed in recent research (Marcora, Bosio, & de Morree, 2008; Marcora, Staiano, & Manning, 2009; Twist & Eston, 2009), perceived muscle soreness and the effect this has upon increased perceived exertion are important considerations for well-being assessment. It has been reported that alterations in perceived fatigue and increased muscle soreness are known to outlast reductions in neuromuscular performance and biochemical markers in rugby league (Twist & Highton, 2013; Twist et al., 2012). This prolonged, lasting alteration in perceived fatigue supports the argument for the use of well-being questionnaires, yet also illustrates the importance of integrating performance measures assessing NMF and with self-report measures. Recent research in elite rugby union by Shearer, Kilduff, et al. (2015) further emphasised the use of WB monitoring as a measure of recovery, via The Brief Assessment of Mood questionnaire (BAM) (a shortened version of POMS), although it did recommend its use alongside endocrine measures and power output.

Despite well-being ratings being common practice in the elite field and being relatively easy to administer at minimal cost, caution should be taken when interpreting results. Limited evidence exists, regarding the relationship between well-being questionnaires and changes in performance, with compliance from athletes decreasing if data collected upon the training dose-

response relationship is not acted upon. Recent research by Roe et al. (2015) presented a CV of 7.1% for WB questionnaires in elite youth male rugby players, which despite being lower than the <10% CV recommended by Buchheit, Lefebvre, Laursen, and Ahmaidi (2011), shows the difficulty of assessing WB scores and therefore warrants consideration when used to assess fatigue post rugby union match play. Practitioners have been noted to gather data on recovery via custom-made questionnaires (Rowse et al., 2009) and it is believed that well-being questionnaires, designed applicable to the sport in question, provide more informative data on the response of the individual than a generic well-being questionnaire. One could therefore argue that the use of well-being questionnaires in team sport settings are especially important, considering that each individual might respond in a different manner, as a result of the training dose administered by the coaches, as was found in the study by Lovell et al. (2013) assessing factors affecting RPE in rugby league.

In addition to designing bespoke questionnaires for athletes, the questionnaire length and frequency of administration should be considered as supported by Halson (2014) in order to maximise compliance. Saw, Main, and Gatin (2015) recommended a multi factorial and multi-level approach to be implanted into athlete self-report measures, to improve efficacy. In addition to the aforementioned considerations, practitioners should be aware that athletes could manipulate well-being data, based upon their estimation of the training load and desire to manipulate any future training planned. Additionally, an athlete's sleep is often rated within fatigue research, yet the reliability of such measures is often questioned, as the length and quality of sleep, for example, are difficult to measure via perceptual measures, despite the importance of a measure such as sleep being used to assess an athlete's readiness. The validity of some of the perceptual measures used by practitioners (such as self-report well-being and rate of perceived exertion) in the research outlined in Table 2.13 is therefore questioned.

2.4.4 Biochemical markers

Assessing fatigue via performance tests such as jump tests, submaximal tests, or sport specific tests is common place within elite settings, yet, as concluded by Twist and Highton (2013), performance tests should only be used when other markers (biochemical and perceptual measures) suggest fatigue. It is, however, important to note that many teams cannot afford to implement biochemical testing and that they therefore utilise performance testing (sub-maximal or maximal) as an alternative means of assessing fatigue. Hormonal concentrations during the recovery period post-training or competition provide important data for practitioners when assessing restoration of performance and associated readiness. Neuroendocrine response to exercise is well documented (Cunniffe et al., 2010; Lindsay, Lewis, Scarrott, Gill, et al., 2015), yet the findings on the resultant fatigue state are contrasting (Cormack, Newton, & McGuigan, 2008; Filaire, Legrand, Lac, & Pequignot, 2004).

Many studies have reported the use of biochemical and endocrine analysis during team sports seasons (Alaphilippe et al., 2012; Crewther et al., 2009; Cunniffe et al., 2010; Hoffman et al., 2002), reflecting the stress and muscle damage that occurs post many team sport movements, with a review of the potential use of urine and saliva tools noted as "the future" in a recent review of non-invasive biomarkers (Lindsay & Costello, 2016, p. 11). Crewther et al. (2009) analysed neuromuscular changes and associated changes in biochemical data post-training for thirty-four professional male rugby players. Correlations were found between salivary testosterone and cortisol values and speed (10 m, 20 m or 30 m sprints; $r = 0.65$, $p < 0.05$);

power, concentric mean ($r = 0.41$, $p < 0.05$), during a 70 kg SJ and 50 kg peak power bench press throw ($r = 0.41$, $p = 0.05$); and strength measures (estimated 1RM) strength for a box squat ($r = 0.39$, $p = 0.05$) and bench press ($r = -0.42$, $p < 0.05$). More recent research in rugby union (West et al., 2014) has, however, noted that no relationships exist between changes in CMJ, biochemical markers (testosterone and cortisol) and mood. These findings have implications for the post-match recovery modalities implemented and the hormone secretion patterns expected. It is, moreover, important to note that practitioners should be aware that the possible reasons for the contrasting results between studies that assess use of biochemical markers in rugby might be based upon methodological differences. For example, the study by West et al. (2014) incorporates data post-match, whereas the study by Crewther et al. (2009) assesses post-training across differing time-points, with different performance measures correlated to biochemical markers being evident within both the studies. The following sub-chapters critically assess commonly used biochemical markers utilised by team sport practitioners and their practicality for use within elite rugby settings.

2.4.4.1 Muscle damage and biochemical response

Research in both rugby league and rugby union (Cunniffe et al., 2010; McLellan et al., 2011b; Takarada, 2003) has shown that the number of collisions/tackles that occur during matches correlates with muscle damage markers, while in soccer the volume of high intensity efforts, many of which include eccentric loads, relates specifically to fatigue and muscle damage (Crewther et al., 2009; Proske & Morgan, 2001). Takarada (2003) noted that the degree of muscle damage in rugby union relates directly to the number of collisions experienced, with McLellan et al. (2011b) noting a 25% reduction in PRFD and 20% reduction associated with a 51% increase in salivary cortisol concentrations, in elite rugby league players. McLellan et al. (2011b) reported that CK values remained elevated for up to five days post-match and that significant correlations were seen between CK values and PRFD and cortisol and peak force PF measured via CMJ. It is, however, important for practitioners to understand that there are differences in the methods used to collect and analyse the biochemical markers mentioned above. For example, blood samples were used to assess immune endocrine markers post-match play within the research by Takarada (2003) and by Cunniffe et al. (2010), yet in the research by McLellan et al. (2011a) they incorporated both blood and saliva measurements. Despite data taken at similar time-points across all the above research, disparities in results taken from both blood and saliva are expected, therefore emphasising the need to compare only data across similar methodological protocols. Reliability of both saliva measures have been reported, with Dabbs (1990) presenting $r = 0.64$ across two days and $r = 0.52$ across seven-eight weeks using saliva testosterone measurements. The important consideration here for practitioners to note is the methodology used. Caution is advised when comparing research where, for example, Coutts, Reaburn, Piva, and Murphy (2007) used plasma testosterone to cortisol measures, whereas West et al. (2014) used salivary measures across similar elite rugby playing populations.

Duffield et al. (2012) and Twist and Highton (2013) discussed studies where significant post-match increases in muscle damage were observed through CK and myoglobin analysis. Similar support for the use of CK analysis in rugby union has been reported by Alaphilippe et al. (2012) and in many rugby league studies (Johnston et al., 2013; McLellan et al., 2011b; Twist et al., 2012), with increases in CK values following six weeks of deliberate overreaching in rugby league (Coutts, Reaburn, Piva, & Rowsell, 2007). An increase in CK has been quantified as a

reliable marker of tissue damage post-match play in rugby league and has been recommended as a marker to monitor recovery (McLellan et al., 2011a), as well as training prescription involving hormone monitoring (Crewther et al., 2009). Some research has reported CK requiring 72 hours to return to baseline values post-rugby (Minett, Duffield, & Bird, 2010; Takarada, 2003). Varying results have, however, been reported for CK, with a CV of 26.1-27% reported between testing days (Roe et al., 2015; Twist & Highton, 2013; Twist et al., 2012). Twist and Sykes (2011) commented that myofibrillar disruption has been reported in some studies (Cunniffe et al., 2010; Takarada, 2003), yet this measure of muscle damage provides no clear indication of muscle function and it is more likely that force generating capacity provides the most appropriate indirect marker of muscle damage.

Despite a large amount of recent research incorporating saliva testing that assesses time-course of changes in immunoendocrine markers in team sports (Beaven, Cook, et al., 2008; Beaven, Gill, et al., 2008; Cormack, Newton, & McGuigan, 2008; McLellan et al., 2010), varied reliability and validity has been noted (Coad, McLellan, Whitehouse, & Gray, 2015; Dabbs, 1990). This poor reliability and subsequent lack of meaningful impact of saliva testing is, therefore, a point to consider for practitioners in the elite field, when making decisions about which testing measures would be best to implement.

2.4.4.2 Hormonal response

T and C are considered reliable markers of a return to endocrine homeostasis post-competition, with T being the dominant anabolic marker of protein signalling and C being an important stress hormone that works against T (Cormack, Newton, McGuigan, & Cormie, 2008; Elloumi, Maso, Michaux, et al., 2003). A rugby match is known to alter the catabolic/anabolic-related hormonal homeostasis towards a predominant catabolic response during the first 48 hours of the recovery process (McLellan et al., 2010). McLellan et al. (2010) also reported that return to normal testosterone to cortisol balance (T:C) is expected within 48 hours of rugby league match play. Cunniffe et al. (2010) reported T:C levels rising above pre-game values and Elloumi, Maso, Michaux, et al. (2003) noted that T:C ratio increased above basal levels for up to five days post international rugby games. Cormack, Newton, McGuigan, and Cormie (2008) discussed the anabolic-catabolic T:C ratio and reported a ratio decrease of 30% as being an accurate indicator of overtraining and that C had a small relationship to performance when assessed alongside CMJ flight time. Filaire et al. (2001), however, did note that caution should be used when using the T:C ratio for NMF assessment as their results did not relate to reduced performance or diagnosed OT when using prescribed 70-75% of VO_{2max} physical training sessions. Conversely, some research (Alaphilippe et al., 2012; Coutts, Reaburn, Piva, & Murphy, 2007) reported that large training loads with insufficient recovery caused reduction in T:C ratio, increased CK activity and decreased glutamine to glutamate ratio.

Buchheit et al. (2013) noted that training load, heart rate data and wellness measures via questionnaires should be used to monitor recovery status, but not the salivary cortisol measures commonly used to assess hormonal balance. When examining the usefulness of selected physiological and perceptual measures to monitor fitness, fatigue and running performance during a two week pre-season training camp in Australian rules footballers, Buchheit et al. (2013) noted significant ($p < 0.001$ for all) day-to-day variations in training load (CV = 66%), wellness measures (6-18%), HReX (3.3%), LnSD1 (19.0%) when utilising a Yo-Yo IR2 test (pre-, mid- and post-training camp). Buchheit et al. (2013) did notice that salivary

cortisol measures did not show practical efficacy (20.0%, $p = 0.60$), further signifying the need for caution when implementing hormonal measures to assess readiness. In addition to day-to-day variations that exist within salivary cortisol, Hayes, Sculthorpe, Young, Baker, and Grace (2014) reported that a large magnitude of change for salivary cortisol (90%) and salivary testosterone (148%) exists, therefore suggesting a biologically significant mean change is difficult to assess. Filaire et al. (2001) similarly reported that decreased salivary T:C ratio does not lead to a decrease in team performance, or perceived wellness, of the players assessed via questionnaire in professional soccer, while more recent research (Shearer et al., 2016) has noted variance in CK correlation with BAM scores in elite under 21 academy soccer players. This is in contrast to previous research that has reported significant changes in C post team sport games (Cormack, Newton, McGuigan, & Cormie, 2008; McLean et al., 2010). Data from both soccer and cycling endurance tests (Filaire, Lac, & Pequignot, 2003; Gastmann, Petersen, Bocker, & Lehmann, 1998) would suggest that instead of the T:C ratio being a warning sign for OTS, it is perhaps only an indicator of short term physiological stress from training or competition. The aforementioned research by Filaire et al. (2001) illustrates the inaccuracy of T and C assessment when using the T:C ratio for NMF assessment, as their results did not relate to reduced performance. When considering the time consuming nature of managing biochemical essays, alongside the inconclusive accuracy of T and C testing alone, the rationale for testing the T:C ratio is further questioned, demonstrating, perhaps, that identification of a single biochemical variable would be more realistic for use in team sport settings. Biochemical testing within elite rugby environments on a regular basis is therefore considered impractical, due to the time commitment, cost, circadian disturbances and lack of rapid feedback involved within such biochemical testing procedures.

2.4.4.3 Metabolic response to rugby game play

Metabolic cost of exercise and the associated EIMD have been researched (Tee, Bosch, & Lambert, 2007), as well as inflammatory response to low frequency neuromuscular fatigue (Twist & Eston, 2009). Mashiko et al. (2004b) noted that rugby union forwards accumulate a catabolic degeneration of muscle tissue due to contact situations, in contrast to backs where metabolism and energy consumption induces fatigue. McLellan et al. (2011b) reported that immediate reduction in neuromuscular function post-match, when assessing jump performance and associated SSC, should be attributed to the metabolic accumulation and depletion of energy sources during performance. Additionally, secondary reduction in NMF was noted by McLellan et al. (2011b) to be more likely to be attributed to the inflammatory processes accumulated as a result of SSC exercises. These varying forms of fatigue have been reported to require differing ingestion of recovery energy sources post-match, where forwards are recommended to include an increased source of protein in order to accelerate recovery (Mashiko et al., 2004b). Ingestion of energy sources (carbohydrates, fats and proteins) has been noted to speed recovery in post-match situations, aiding in the replenishing of glycogen stores and repair of muscle damage and therefore speeding restoration of performance (Howarth, Moreau, Phillips, & Gibala, 2009; Minett et al., 2010; Moore et al., 2009). This is discussed in more detail in Chapter 2.5.1.7. Both substrate depletion and muscle damage are considered to be major inhibitors of hastened restoration of performance and general feeling of recovery post-rugby (Casiero, 2013) and are therefore an area of importance for practitioners working with teams competing on a weekly basis where the need to hasten recovery and improve readiness for the next match are essential.

It has previously been reported by Bangsbo, Iaia, and Krstrup (2008) that fatigue towards the end of soccer match play is muscle glycogen depletion related. It could, however, be argued that this glycogen depletion would not affect jump performance immediately post-match and that instead it is more likely that muscular fatigue from movement patterns completed within game situations would affect jump performance. The exercise duration associated with rugby union match play is too short for any glycolytic contribution to be required and hence jump-test markers are likely to be affected by glycogen depletion fatigue immediately post-match, therefore emphasising to practitioners that other areas of fatigue post-match, such as muscle damage, warrant more investigation than metabolic responses. Glutamine to glutamate ratio is one biochemical marker that has been considered to be a good indicator of tolerance to training assessing free amino acid concentrations, showing a reduction in glutamine/glutamate ratio thus representing its training intolerance in rugby league (Coutts, Reaburn, Piva, & Rowsell, 2007). To the author's knowledge no data has been reported on optimal glutamine/glutamate ratios in team sports such as rugby, although Halson et al. (2003) have observed a threshold of < 3.58 as being indicative of overreaching in cycling. It is of importance for practitioners to note that factors such as nutritional diet and deliberate glutamine supplementation could affect resultant free amino acid concentrations. Therefore, caution should be advised when using glutamine/glutamate ratios to assess training tolerance in team sport settings.

2.4.4.4 Considerations for biochemical testing

Although biochemical markers of fatigue provide more objective measures of homeostatic disturbances, the expense associated with hormonal testing and the expertise needed to perform such tests make them unrealistic for assessment in many club rugby union teams. One could also conclude that hormonal markers as measures for assessment in rugby union are not practical in a team environment, where daily training and the large number of players in a playing roster, would inhibit hormonal marker testing on a progressive basis. Another important consideration for practitioners is standardisation of biochemical testing protocol. Common issues that are known to be utilised and to affect the reliability of biochemical testing include; ambient temperature, hydration status, diet, glycogen content, previous exercise and sampling procedures. These issues are summarised by Halson (2014, p. 143) who notes "the use of biochemical, hormonal and/or immunological measures as indicators of internal load is currently not justified based on the limited research in this area". When considering the low reliability (Hoffman et al., 2002) and large intra-individual differences (Maso et al., 2004) associated with biochemical testing, practitioners should instead focus upon markers from performance tests, which are specific to the task completed and are more practical in nature.

Further lack of support for biochemical testing arises from research assessing biochemical and hormonal responses during an intercollegiate American football season (Hoffman, Kang, Ratamess & Faigenbaum, 2005, p. 1237), where players were noted to develop "contact adaptation" as they progress through the competitive season. As supported by Twist and Highton (2013), due to the inhibitive and expensive nature of biochemical testing a more rounded appraisal of player fatigue and subsequent readiness to train is recommended for use in many sporting environments. Considering that it is not uncommon for hormonal and neuromuscular factors not to correlate with performance tests such as those detailed above, practitioners should perhaps use biochemical testing in conjunction with movement data (GPS) and heart rate data, which have been noted to have high validity and reliability (Casamichana et al., 2013) in addition to perceptual measures (RPE) which would therefore aid in better

quantifying global fatigue.

2.4.5 Heart rate derived measures

A change in heart rate (HR) due to autonomic nervous system response is a possible indication of adaptation to training stress. As a coach, a simple and effective means of assessing player readiness is paramount, with heart rate derived measures providing recent literature to aid practitioners attempting to quantify load (Bosquet et al., 2008). Training load assessment via heart rate measures is well-documented and validated in endurance sports (Plews, Laursen, Kilding, & Buchheit, 2012; Plews, Laursen, Stanley, Kilding, & Buchheit, 2013), yet this method of assessment has only been researched in a few team sport scenarios (Buchheit et al., 2013; Coutts et al., 2003). Most HR data from rugby concerns match situations, where data has been used to describe the intensity and energy expenditure of players throughout games, thereby helping to guide practitioners in training prescription. Recently, however, many practitioners have used heart data to guide recovery and restoration post-performance (Cornforth et al., 2014).

2.4.5.1 Resting heart rate

Perhaps the simplest heart rate derived measure of fatigue is that utilising resting heart rate (RHR), with overreaching in elite athletes noted to correlate with increased RHR (Kuipers & Keizer, 1988) when reviewing elite athlete case studies. Lack of support for the use of resting heart rate comes from Bosquet et al. (2008), who noted trivial increases in RHR as an indicator of overreaching, when conducting a meta-analysis upon the effect of overload training on RHR. Bosquet et al. (2008) did, however, observe larger increases in RHR post short-term training loads, therefore representing RHR as a valid indicator of short-term fatigue. Despite RHR being a relatively simple practice to implement, its use in team sport settings is limited and requires future research to confirm validity. Recent research by Plews, Laursen, Kilding, and Buchheit (2013), evaluating training adaptation and comparing methodological practices from heart-rate derived measures, recommend the practice of averaging weekly RHR values when assessing adaptation to training.

2.4.5.2 Heart rate variability

One of the most increasingly used methods of assessing cardiac readiness via heart rate measures is the application of heart rate variability (HRV) assessment, which was first used in clinical practice almost forty years ago. HRV assessment has received significant praise in recent years (Bosquet et al., 2008; Stanley, Peake, & Buchheit, 2013) and has been applied in many elite sporting settings (Buchheit et al., 2013; Plews, Laursen, Stanley, et al., 2013; Tian et al., 2013), with its reliability confirmed in a study by Parrado et al. (2010). However, the meta-analysis provided by Bosquet et al. (2008) noted day-to-day variability of HRV measures, with contrasting evidence presented for its accuracy and practicality to reflect changes in performance in elite sport settings (Buchheit et al., 2013; Plews, Laursen, Stanley, et al., 2013; Tian et al., 2013). Additionally, in a more recent systematic review of HRV use (Bellenger et al., 2016), it was noted that alongside post exercise HRV assessment demonstrating positive adaptations to training, increases in HRV can also occur in response to overreaching.

Modulation of the heart and the associated change in interval between heartbeats is controlled by the autonomic nervous system (ANS), with R-R interval used as an index of autonomic nervous system responsiveness. The cardiovascular system can be viewed as a well-structured function designed to achieve dynamic stability of the heart. HRV measures fluctuations in HR,

with a high variability in HR signal in a healthy individual suggesting well-functioning autonomic control mechanisms (Pumprla, Howorka, Groves, Chester, & Nolan, 2002). Conversely, a lower variability of the heart is often an indicator of insufficient adaptability of the autonomic nervous system, therefore potentially implying compromised health in an individual. Cardiovascular stability is achieved by the autonomic system controlling HR and other factors, by reacting to events such as ischemia and changes in physical or mental activity. In the case of sport, ischemia is present due to a restriction of blood to the tissues during exertion and means that heart rate has to adjust accordingly. Within the dynamic stability of the heart mentioned above, parasympathetic activation slows down the heart, while sympathetic activation results in an increase in HR. HRV is affected by the balance between both the sympathetic and parasympathetic responses and the effect this has upon the nervous systems. HRV represents the continuous oscillation of the R-R intervals around its mean value, providing non-invasive data about the autonomic regulation of the heart in real life situations and is most commonly assessed in resting states (Task Force Of The European Society Of, The North, Society Of, & Electrophysiology, 1996). The frequency bands associated with HRV analyses via ECG correspond to differing frequency levels with low frequency (LF), with sympathetic activity occurring between 0.04-0.15 Hz and high frequency (HF) parasympathetic activity occurring between 0.15-0.4 Hz.

Contrasting findings have been reported regarding HRV during OT periods (Aubry et al., 2015), with both increases and decreases observed. Many authors have recommended the use of weekly and rolling averages of HRV data, when assessing autonomic balance and associated player readiness (Daanen, Lamberts, Kallen, Jin, & Van Meeteren, 2012; Halson & Jeukendrup, 2004; Plews et al., 2012; Plews, Laursen, Stanley, et al., 2013). Tian et al. (2013) reported two distinct HRV fluctuation patterns when assessed against the training load prescribed, in their study involving overreaching in female wrestlers. Firstly, they noted that when HRV indices were reduced, the LF:HF ratio was significantly increased, representing a period where training load was too high and recovery time too small. Using time-domain analysis, SDNN (standard deviation of the normal to normal intervals), RMSSD (the square root of the mean squared difference between adjacent N-N intervals) and HF can be recorded for statistical and geometrical analysis of R-R interval data. Secondly, Tian et al. (2013) reported that when HRV indices increase, the wrestlers were reported to be under too much psycho-emotional stress, demonstrating that both physical and psychological stimuli need to be considered when assessing athlete readiness. It can therefore be concluded from the research by Tian et al. (2013) that NFOR can be both sympathetically and parasympathetically driven, giving coaches greater insight into athletes physical and emotional current functional state. However, limited research illustrating the effectiveness of HRV measures that assess changes in performance in team sport settings exists.

Many team sports training weeks involve workouts that do incorporate a cardiovascular response and instead focus on strength and power elements, many of which are based in the gymnasium. Despite HRV measures being shown to reflect acute fatigue (Mourrot, Bouhaddi, Tordi, Rouillon, & Regnard, 2004), the lack of cardiovascular response and associated lack of research in HRV practices in team sport settings means that HRV use in rugby is limited. Many team sport practitioners have relied upon the aforementioned neuromuscular function tests such as CMJ and training load monitoring, instead of the use of HRV, or other HR derived measures. Some HRV research in rugby union does exist. For example, Edmonds et al. (2013)

note that participants in their rugby league study who exhibited greater cardiac randomness might be able to train to a higher workload in future training weeks compared with players with reduced cardiac control. It could, however, be argued that there were multiple limitations to the study by Edmonds et al. (2013), as the sample size was small and the subjects were all youth team players who might exhibit different HRV responses to that of elite full-time professional rugby players, who have greater training age and associated match fatigue. Additionally, within the study by Edmonds et al. (2013) the monitoring period was limited to 4-5 days, meaning exact measures of HRV data cannot be compared to other studies that would incorporate longer research periods.

Bara-Filho et al. (2013) concluded that HRV values were an effective means of assessing adaptation to a training schedule with a stable or increasing HRV indicating good recovery and maintenance of training volume. Buchheit (2014) recommends that a consideration and understanding of the context of training load imposed on the players in team sport scenarios is important. In contrast to endurance related sports, where HR derived data and blood lactate levels are commonplace (Plews, 2014), the impact of training load on HR response is still to be examined. In team sports, “the load arises from a myriads of biological systems stressed simultaneously” (Buchheit, 2014, p. 8), therefore emphasising the need for further investigation. The need for repeated measures analysis of HRV data in contrast to isolated measures was emphasised in recent research (Le Meur et al., 2013; Plews, Laursen, Kilding, et al., 2013), with a minimum of three HRV assessments per week recommended for accurate assessment of training status. Correlations have been reported in endurance athletes between HRV indices, running performance and athletes identified as overreached (Leti & Bricout, 2013). Buchheit (2014) also recommended only considering change that is practically meaningful and clearly greater than the significant worthwhile change (SWC). The calculation of magnitude of SWC associated HR measures are less straightforward than other performance tests, due to the individual nature of HR derived data and the associated training load which has perhaps initiated the HR change. This change in HR indices could derive from isolated training sessions or perhaps be in response to a whole training phase, further emphasising the individualised nature of HR data. Another factor that may influence use of HRV recordings is the recommendation by Plews et al. (2014) that lesser trained individuals require more frequent HRV recordings (> 5 days), as CV was shown to be $10.1 \pm 3.4\%$ for recreational runners compared to $6.7 \pm 2.9\%$ for triathletes.

In order to adapt training based upon measurements requires confidence in the data, meaning that recent research has focused upon day-to-day variations of indices. The study by Edmonds et al. (2013) using rugby league players is believed to be the first to examine the influence of daily training and matches on day-to-day variations in HRV within a competitive playing season. This study by Edmonds, et al., (2013, p 3) reported that during a normal week of training, including a competitive match, participants “exhibited a shift in cardiac autonomic balance towards lower HRV on game day, reduced HRV and predominant sympathetic modulations for 1-2 days post-match, and a reduced supine-to standing HRV response for up to four days after a game.” This research shows that rugby players experience HRV fluctuations throughout a training week and maintain significant cardiovascular stress for up to four days after a match. HRV data presented from rugby players post-match should therefore be considered for subsequent planning of training weeks, as HRV responses could significantly affect future game performance throughout a competitive season. The research by Edmonds et al. (2013) and

McLean et al. (2010) supported suppressed metabolic and cardiac systems respectively for at least two days post rugby league game. As mentioned above, Edmonds et al. (2013) concluded that HRV measures from supine to standing remained depressed for two days post-match and that this orthostatic analysis may provide more accurate and insightful measures of cardiac autonomic reactivity and recovery compared to absolute HRV measures.

A recent contact sport study assessing judo athletes (Morales et al., 2014) utilised HRV for monitoring stress, presenting interesting results. Similarly to rugby union Morales et al. (2014) noted that, in judo, difficulty arises when attempting to quantify training load because of the characteristics of the sport. The same difficulties are apparent in rugby union, where opponents, weather, volume of contact training completed and intensity of games all add to the questionable quantification of the training load completed. Some aspects of a rugby player's training week are easier to quantify, such as strength and conditioning sessions, yet these sessions would not represent the whole training week prescribed to the player with the associated effect this can have upon HRV. Morales et al. (2014), therefore, recommend further analysis of HRV training load responses in sports such as wrestling, rugby and other contact sports.

Stanley et al. (2013) noted that individuals with greater fitness levels show more cardiovascular resilience to training stress, with periods of supercompensation being the optimal period for greatest performance gain. Stanley et al. (2013) also noted that data on the cardiac parasympathetic response following strength/resistance training is limited, as aspects such as muscle soreness cannot be tracked by cardiac parasympathetic activity. It was, therefore, proposed by Stanley et al. (2013) that the level of perceived neuromuscular and musculoskeletal strain induced by the training session should be included within the recovery period. Chen et al. (2011), however, noted that parasympathetic reactivation occurred at a slower rate amongst weightlifters than was seen for endurance training (Iellamo, Pigozzi, Spataro, Lucini, & Pagani, 2004). Chen et al. (2011) commented that this discrepancy is probably due to weightlifting being a sport that involves more muscle trauma than endurance sport. The anaerobic nature of weightlifting means that neuromuscular repair after training can demand more energy and therefore a subsequently longer recovery time.

Rugby union could be considered a sport that involves both aerobic and anaerobic aspects from both training and games perspectives; with the resultant effect this has upon parasympathetic and sympathetic response post-match and training being a significant area of interest for future research. One monitoring tool that does claim to include HRV analysis alongside CNS and metabolic reaction index (MRI) (which is reported to be influenced by muscle damage) is the *Omegawave*. If the claims are valid, a monitoring tool such as *Omegawave* would present a more holistic view of a rugby player's readiness (considering the associated aerobic, anaerobic and blunt trauma aspects) and reflect changes in performance, then its practicality and usefulness in elite team sport settings will be difficult to ignore.

2.4.5.3 Heart rate recovery

In contrast to HRV, which provides information on the modulation of HR, heart rate recovery (HRR) is considered a marker of parasympathetic tone with Daanen et al. (2012) recommending it as a training monitoring tool to access changes in high intensity exercise performance (Vernillo et al., 2015), thus assessing cardiac parasympathetic activity in the immediate minutes post-exercise. However, in a recent investigation of the minimal exercise

intensity required for HRR assessment, Le Meur, Buchheit, Aubry, Coutts, and Hausswirth (2016) recommended sub-maximal intensity for monitoring endurance athletes' responses to training. While HR during exercise measures cardiac load, HRR reflects autonomic nervous system function, indicating the body's capacity to respond to exercise. HRR measures the rate at which HR declines at the cessation of exercise, with Hedelin, Kentta, Wiklund, Bjerle, and Henriksson-Larsen (2000) noting that assessing maximal HR during an incremental run test is an easy way to determine overtraining related variations in maximal performance. Support for HRR guided training programs was presented by Buchheit et al. (2008) who noted HRR to be more sensitive to training induced changes than HRV indices, and recommended it for combined use with HRV analysis in order to assess post-exercise recovery. Despite previous research, assessing HRR, showing conflicting results (Vicente-Campos, Lopez, Nunez, & Chicharro, 2014), Buchheit and Gindre (2006) proposed an 8 ± 5 bpm difference in HRR recorded over the 60 second period post exercise to be meaningful for investigation.

As reported in previous research (Buchheit et al., 2008) the most common way of assessing HRR was to assess the absolute difference between the final HR at exercise completion and the HR recorded after 60s of recovery (HRR_{60s}). Aubert et al. (2003) described that, during exercise, heart rate increases due to both a parasympathetic withdrawal and an augmented sympathetic activity. In a recent review of HRR and changes in training status (Daanen et al., 2012), it was proposed that although HRR improves with training status, it remains unchanged until a period of decreased training is implemented. In a study by Buchheit et al. (2013) examining selected physiological and psychometric measures for monitoring fatigue, a submaximal five-minute running and recovery test was utilised at the start of each training session. In this study, involving elite soccer players, training load variations were seen to correlate with heart rate exertion (HREx) and vagal related HR index (LnSD1) measures and HREx were seen to decrease as the players progressed through the pre-season period, demonstrating that the effectiveness of a submaximal performance test was warranted. It is, however, important to note that the regular implementation of a five-minute running and recovery test would be impractical in many team sports settings, due to logistical constraints.

Previous studies in team sports settings utilising HRR have produced contrasting results (Daanen et al., 2012; Lamberts, Swart, Capostagno, Noakes, & Lambert, 2010; Lamberts, Swart, Noakes, & Lambert, 2009, 2011; Vicente-Campos et al., 2014), mainly due to the wide variation in baseline fitness of athletes measured and exercise protocols used. Methodologies currently used to measure HRR include measuring the number of beats recovered within a given time period (e.g. 60 s) and signal modelling via linear models. Other methodologies using HR derived data to measure fatigue include interval running tests and the Zoladz test (Schmikli et al., 2011), where elevated HR and performance drop were indicators of overreaching. Limitations of HRR use and the variables and methodology used within it, include signal modelling limitations and the need for software that is often unavailable to practitioners. Monoexponential modeling has been reported to capture more effectively the overall HR response, with correlations noted in endurance performance change when assessing HRR variables (Daanen et al., 2012). By contrast, team sport changes in HRR have not correlated with performance and have presented correlations of lower magnitude than observed in HR exertion (Buchheit, 2014). Further support for HRR was presented by Cornforth et al. (2014) where HRR showed an increase in fitness correlating ($p = 0.016$) with 2km time trial results improving in elite Australian Rules football players. Reliability of post-exercise HRV measurements was noted by Buchheit et al.

(2008), with an SEM of 14.2 ms for post-exercise rMSSD, while HRR showed a SEM of 12.6 ms (Buchheit, Papelier, Laursen, & Ahmaidi, 2007). Cornforth et al. (2014) reported that HRR was a reliable ($r=0.92$) and valid for the assessment of training load with low intra-individual variation, while Lamberts et al. (2010) noted a CV of 95% when assessing HRR%. Added to this Cornforth et al. (2014) noted that an adapted version of the Heart rate Interval Monitoring System (HIMS) test has sufficient precision to detect changes in fitness and training load status in Australian Rules footballers. This research by Cornforth et al. (2014) supports the views of previous researchers (Buchheit & Gindre, 2006; Lamberts et al., 2009) that training load influences HRR and that aerobic fitness contributes to an increase in HRR%.

2.4.5.4 Considerations for heart rate derived data and responses to exercise

Despite HR derived data being one of the most easily accessible physiological measures available, changes in HR and HRR are inaccurate (Bagger, Petersen, & Pedersen, 2003) with daily variation in HR reported to be up to 6.5% for submaximal HR and noted to be affected by factors such as hydration, caffeine intake, environment, stress and medication (Vukovich, Schoorman, Heilman, Jacob, & Benowitz, 2005). Resultant changes in HR as a consequence of exercise can represent both a positive and negative training response, thereby supporting the view that the use of HR for assessing readiness and possible maladaptation to training, yet also emphasising the difficulty for interpretation. Due to the reluctance of many practitioners within team sport settings to administer maximal HR measures during competition phases of the season, more research is needed into what constitutes meaningful change in sub-maximal HR performance tests. From the research above it is evident that heart rate derived measures hold the potential to assess accurately internal load. Heart rate derived measures were therefore considered for future use within this research, with the performance measure implemented likely to be the measure that is most applicable to the elite rugby setting in question.

2.4.6 Summary

In consideration of all of the above performance tests, methodological and logistical considerations often dictate the choice of assessment. Despite performance tests being easy to implement in order to assess individual training response, the main limitation of some of these tests is that the information obtained does not explain the reason for the performance reduction. In light of the performance tests reviewed above, jump testing, “off feet” maximal tests on a cycling ergometer and heart rate derived measures (HRR and HRV) seem the most applicable for further study within this research. Jump testing, for example, needs further investigation in order to ascertain which parameters are most informative when monitoring fatigue. When sport specific parameters sensitive to fatigue are identified, from performance measures such as jump testing, the meaningful change and expected typical error will further guide practitioners on the meaning of test results. In contrast to jump testing, maximal and sub-maximal performance tests (“off feet” and “on feet”) are less frequently used within team settings and reliability of such tests are therefore lacking. It is, however, expected that as future sport specific technological advances for readiness testing are developed, the focus of fatigue measures post game will continue to investigate the use of over ground “on feet” and gym based “off feet” performance tests, alongside the implementation of jump testing. Similarly, the use of heart rate derived measures, will likely continue, as unlike jump testing and maximal and sub-maximal performance tests, heart rate derived measures present a true representation of internal load and therefore may be of more interest to practitioners.

2.5 Strategies used to Enhance Restoration of Performance and Recovery

Due to the match demands outlined above and the need to attempt to restore performance as soon as possible post-match, a necessity exists to utilise strategies that would enhance restoration of performance in the days post-match. As examined below, many short-term fatigue management strategies exist that enhance restoration of performance in the days post-exercise, where the relevance and effectiveness of each modality depends upon the sport in question, the practical ability of the practitioners to implement such strategies within the environment and the compliance of the athletes.

2.5.1 Commonly used recovery modalities

Sports scientists and physiologists have routinely pushed the boundaries of science in elite sport by implementing recovery strategies designed to improve readiness (Gill et al., 2006). A balance between training or competition stress and recovery needed to maximise performance is one of the most researched areas in modern sports science, with contrasting evidence for the use of varying intervention strategies (Crystal, Townson, Cook, & LaRoche, 2013; Dawson, Gow, Modra, Bishop, & Stewart, 2005; Rowsell et al., 2009). Short turnaround times between games, the multifaceted nature of professional team sport athletes' training, match and commercial requirements all mean that there is considerable demand on players' time. Knowledge of proven and time-efficient recovery strategies and protocols are, therefore, paramount. As mentioned by Cook, Kilduff, and Jones (2014), during competition phases, team sport athletes are in a cyclic state of adaptation and recovery between games and training. Recovery modalities have subsequently been used to hasten the recovery process outlined in Figure 2.2, yet as explained above, considering that recovery is a return to resting function and physical performance, this is sometimes unrealistic.

Although recovery is considered of extreme importance within team sport settings, both practitioners and athletes often ignore it. The high level of impacts and the metabolic cost involved in a sport such as rugby, are some of the likely contributing factors to the physiological and mechanical stress associated with EIMD. Many team sports conduct recovery sessions the day after a match, yet the protocol and preferred modality for a sport such as rugby union vary considerably. Nedelec et al. (2013) concluded that scientific evidence to support the use of many recovery strategies is lacking. Difficulties in determining efficacy of recovery strategies are mainly due to methodological issues, yet research by Lindsay, Lewis, Gill, Gieseg, and Draper (2015) notes that immediate post-game recovery intervention, following a game of professional rugby union, may be the most important aspect of psychophysiological player recovery. Despite a 57% increase in salivary cortisol ($p < 0.001$), noted by Lindsay, Lewis, Gill, et al. (2015) when assessing the effect of varied recovery interventions on markers of psychophysiological stress in professional rugby union players, no difference was observed in the inflammatory response 36 hours post-match between different protocols, yet the effectiveness of immediate post-match recovery intervention was considered key. The need to research recovery practices in rugby union is therefore of importance to practitioners aiming to improve player readiness between games, where supposed altering of muscle tissue temperature and increased blood flow aid recovery from EIMD and related muscle soreness.

2.5.1.1 Ice baths and contrast water therapy

The use of water therapy to aid recovery is probably the most commonly used recovery modality, with both contrast water therapy (CWT) and cold water immersion (CWI) used by many sports teams (Webb, Harris, Cronin, & Walker, 2013). Exposure of athletes to cold water aids in reducing oedema through the vasoconstriction and vasodilation response of blood vessels to the changes in temperature experienced. The benefits of water therapy are most likely due to a combination of the water temperature and hydrostatic water pressure. In an extensive literature review, Nedelec et al. (2013) proposed that CWI is an effective recovery strategy during acute periods of fixture congestion in soccer. Further support for CWI as a modality to provide beneficial effects on performance was noted by Pournot, Bieuzen, Duffield, et al. (2011), when assessing its influence on blood markers (inflammatory markers, haematological profile and muscle damage) post running treadmill exercise. In addition, perceptions of fatigue and leg soreness were reported as reduced with the use of ice baths throughout a soccer tournament (Rowse et al., 2009), when assessed via questionnaire. Additionally, research by Al Haddad, Parouty, and Buchheit (2012) reported the benefits of ice baths upon subsequent sleep following intense training days and emphasised that CWI was not just to be used to reduce DOMS. However, the small sample size ($n = 8$) and the collection of sleep data via subjective questionnaires within the research by Al Haddad et al. (2012) can be questioned.

Recent literature involving two studies assessing muscle adaptation as a result of CWI has emerged (Roberts, Raastad, Cameron-Smith, Coombes, & Peake, 2014; Yamane, Ohnishi, & Matsumoto, 2015). These studies have doubted the effects of ice baths or CWI on long-term muscular performance and attenuated long-term gains in both muscle mass and strength. Blunted activation of key proteins and satellite cells was noted in skeletal muscle for up to two days after strength exercise, highlighting this as an area of much needed future research, especially in rugby union where muscle hypertrophy is key to maintaining muscle mass. It is, however, important to note that these studies only analysed resistance training in active, but not elite subjects and therefore more research is necessary before conclusions can be drawn on the relevance of CWI in elite rugby settings. Within a recent systematic review and meta-analysis of cold applications for recovery in adolescent athletes by Murray and Cardinale (2015), it was proposed that positive effects of CWI to reduce DOMS are scarce, with more work warranted to assess effectiveness. This lack of support for CWI was also noted in elite weightlifting settings, where Schimpchen et al. (2016) displayed no significant differences in a snatch pull movement, blood parameters or subjective ratings of fatigue when using a randomised cross-over study design, therefore again questioning CWI use in elite settings. Schimpchen et al. (2016) did, however, note that inter-subject differences do exist as a result of CWI, and that its application should be considered on a case-to-case basis.

In a critical appraisal of three different recovery strategies post rugby league game, Webb et al. (2013) reported that CWI and CWT recovered jump height performance, reduced muscle soreness and reduced CK levels post-match, when compared with active recovery. Higgins, Heazlewood, and Climstein (2011) noted the benefit of CWT for enhancing recovery in rugby union, as represented by subjective well-being reports. Contrasting views upon cold water therapies such as CWI and CWT are shown by the research of Montgomery et al. (2008) who noted CWI as superior to CWT, whereas, conversely, Webb et al. (2013) noted CWT as superior to CWI. In a meta-analysis of CWI (Leeder, Gissane, van Someren, Gregson, & Howatson, 2012),

little effect was shown for strength exercises, yet a positive response was noted for exercises that involved stretch-shortening movements. Specifically in rugby union, ice baths prescribed as cold therapy to enhance recovery between games have illustrated contrasting results (Bleakley et al., 2012; Higgins et al., 2011; Takeda et al., 2014), with negative effects of CWI reported by Higgins et al. (2011) and the positive effects of CWT reported by Gill et al. (2006). Gill et al. (2006) reported enhancement of CK clearance with the use of CWT while recommendations for repeated application of CWI was reported by Montgomery et al. (2008) as the most beneficial response. By contrast, Higgins et al. (2011) noted a detrimental effect of ice baths on players performance when recovering from training and competition. These results illustrate the conflicting evidence for ice baths and contrast water therapy. However, considering the simplicity and low cost with which this intervention strategy can be implemented this modality will, likely, continue to be utilised frequently within rugby.

2.5.1.2 Whole Body Cryotherapy (WBC)

WBC is a cold exposure recovery strategy that, although inexpensive in nature and difficult to administer is being used by many athletes throughout the elite and recreational sports world (Hauswirth et al., 2011; Pournot, Bieuzen, Louis, et al., 2011). WBC was proposed over thirty years ago for use as treatment for many inflammatory diseases, with a significant volume of recent literature detailing the topic (Bleakley, Bieuzen, Davison, & Costello, 2014; Costello et al., 2015; White & Wells, 2013). This therapy consisted of exposure to extremely cold air maintained at -110°C to -140°C in special temperature-controlled cryochambers, generally for two minutes and typically initiated within 24 hours of exercise completion. The use of cold modalities such as ice packs and the physiological effects of such practices are well established (Costello, Algar, & Donnelly, 2012). In elite sport the use of WBC has gained significant praise (Galliera et al., 2013) as a method to improve musculoskeletal trauma following training or match play scenarios. Additional recent support for the use of WBC was noted by Schaal et al. (2015) where ten elite swimmers reported reduced signs of FOR, such as reduced sleep quality and increased fatigue, and where WBC was therefore recommenced during periods of intense competition preparation.

The positive effects of WBC have been reported in a literature review by Banfi, Lombardi, Colombini, and Melegati (2010) and WBC is therefore considered by many practitioners to be a procedure that facilitates athletes' recovery and carries no known negative effects. WBC has been reported to influence hormonal modifications, where the body's adaptation to the cold stress applied or experienced, shows an increase in noradrenaline (norepinephrine) (Banfi et al., 2010). Physiological changes have been reported in immunology (venous blood samples) and anaerobic capacity (20 s Wingate test) (Klimek, Lubkowska, Szygula, Chudecka, & Fraczek, 2010), yet these forms of physiological adaptation require a sufficient number of sessions (at least ten) for change to be seen. Additionally, Schaal et al. (2013) reported positive effects of WBC upon parasympathetic reactivation (measured via HRV), which suggests systemic recovery from the training stress imposed. Few studies have, however, justified the effectiveness of WBC as a recovery modality that positively influences athlete readiness to train. Recent research, promoting the use of CWI instead of the application of WBC when assessing its influence upon accelerating recovery kinetics (Abaïdia et al., 2016). Bleakley et al. (2014) concluded that despite WBC being regarded as a superior mode of cooling, due to the extreme temperatures involved, there is no evidence to suggest that WBC has any advantages over other forms of cryotherapy. Bleakley et al. (2014) noted that the poor thermal conductivity of air

prevents subcutaneous and core body cooling. In addition, White and Wells (2013) noted that the effectiveness of WBC remains ambiguous, as the methodology used, protocol undertaken and performance measures assessed throughout WBC studies are so varied in nature that no clear agreement can be concluded.

2.5.1.3 Compression garments

Compression garments have become increasingly prevalent in team sport settings, with the aim of enhancing recovery in the days post-training and games (Davies, Thompson, & Cooper, 2009). These compression garments are often tight fitting elastic fabrics that are expected to enhance muscle recovery by exerting pressure on limbs covered by the garments, by improving blood flow and reducing inflammation. Despite conflicting results, compression garments are used to limit the damage created by exercise, with reduced pain relief and altered inflammatory responses being the focus of administration (Davies et al., 2009; Jakeman, Byrne, & Eston, 2010). Support for the use of compression garments comes from Jakeman et al. (2010), with perceived reduction in muscle soreness as a result of wearing compression garments being claimed to be a significant factor when recovering from EIMD in young, active females.

In contrast to the positive evidence above, Montgomery et al. (2008) noted that the application of compression garments had little advantage in enhancing muscle damage in the days post basketball tournament. Additionally, no performance improvements were noted within recent research, neither upon peak power output (Duffield et al., 2008) following intermittent exercise nor upon CMJ performance (Davies et al., 2009) following drop jump training. However, in a systematic review and meta-analysis conducted by Hill, Howatson, van Someren, Leeder, and Pedlar (2014), evaluating the efficacy of compression garments across twelve studies, a moderate effect was noted on measures of DOMS (95% CI 0.236 to 0.569, $p < 0.001$), muscular strength (95% CI 0.221 to 0.703, $p < 0.001$), muscular power (95% CI 0.267 to 0.707, $p < 0.001$) and CK presence (95% CI 0.171 to 0.706, $p < 0.001$), therefore indicating the potential effectiveness of compression garments in enhancing recovery from muscle damage. In a more recent systematic review and meta-analysis by Marqués-Jiménez, Calleja-González, Arratibel, Delextrat, and Terrados (2016) it was noted that compression garments had no effect upon CK (standard mean difference = -0.98), whereas in contrast, blood lactate concentration was improved due to compression garment administration (standard mean difference = -0.52), therefore illustrating the need for further research.

In rugby union specifically enhanced CK clearance was reported by Gill et al. (2006) as a result of players wearing full leg compression garments for 12 hours post-match in contrast to using passive recovery methods. It is also of importance to note that the use of compression garments alongside electrostimulation improved perceived recovery, compared to wearing compression garments alone (Beaven et al., 2013). Current research into the use of compression garments shows no beneficial effects when compared to active recovery and contrast water therapy (Gill et al., 2006), yet compression garments are a modality that provides an easy to administer strategy in team sport environments where recovery takes place while travelling to and from games. Considering the possible placebo effect of improved perceptual feeling as a result of wearing compression garments, along with the relative small cost implications of implementing compression garment use into team sport settings, this is a recovery modality that should potentially be included within a rugby player's recovery strategy. It is, however, advised that compression garments should be administered alongside other recovery strategies and incorporated when appropriate within the hours and days post exertion (Hamlin et al., 2012).

2.5.1.4 Active recovery

In an attempt to reduce DOMS, many sporting teams commonly complete a post-match “active recovery” session incorporating light aerobic activity (Kinugasa & Kilding, 2009; Nedelec et al., 2012, 2013). These sessions often include light stretching and movement to hasten restoration of performance in the days post-match and prior to the preparation for the next match commencing. The incorporation of active recovery practices is considered to be a process that accelerates the removal of metabolites and increases blood flow, therefore reducing post-match recovery time (Calder, 2000). The most commonly used activities for recovery sessions within team sports are; low-intensity swimming, walking and cycling, which are believed to increase the removal of metabolic waste products such as lactate, hydrogen ions and potassium produced during exercise (Fairchild et al., 2003). However, the efficacy of active recovery for improving subsequent performance was questioned by Robson-Ansley, Gleeson, and Ansley (2009) in their review of fatigue management strategies, due to the notion that that active recovery protocol would slow glycogen resynthesis post exercise. When comparing the effectiveness of recovery strategies in rugby union (CWT and compression garments) twenty minute low intensity recovery sessions were noted by Gill et al. (2006) as an effective measure to reduce inflammation and remove metabolites. More recently, Peake et al. (2016) recommended active recovery as being just as effective at reducing inflammation or cellular stress in muscle after a bout of resistance exercise as CWI. In a study assessing the intensity at which blood lactate disappears following a 50 second maximal cycling test, moderate intensity recovery sessions were noted as more effective than passive recovery, yet a combination of low and high intensity recovery practices were considered to have no more effect than a low intensity session that involves activities less than 35% $\text{VO}_{2\text{max}}$ (Dodd, Powers, Callender, & Brooks, 1984).

Lum, Landers, and Peeling (2010) noted the positive effects of swimming based recovery sessions on subsequent running performance, while Suzuki et al. (2004) reported reductions in post rugby match psychological stress as a result of swim recovery methods. However, the study by Lum et al. (2010) used triathletes during a maximal run test ten hours post high intensity running to measure the effectiveness of swim recovery and this is therefore limited in relevance to rugby union where maximal testing has already been identified above as unrealistic for use in elite rugby settings. Despite the study by Suzuki et al. (2004) involving university level rugby players, its relevance to elite rugby union is evident. Physiological (blood biochemistry) and psychological (POMS scores) were used to assess recovery in the days post-match, showing no adverse physiological effect of swim recovery implementation and an increased psychological recovery due to enhanced relaxation. Hydrostatic pressure from water pressing against muscle tissue, involved within swim sessions is believed to restore performance at a greater rate than other forms of active recovery, with evidence presented by Lum et al. (2010) showing that levels of C-Reactive Protein in blood samples decreased as a result of swim based recovery sessions. It is, however, important to note that support for active recovery methods are conflicting, with a lack of support presented by Choi, Cole, Goodpaster, Fink, and Costill (1994). Using three, 1-min exercise bouts at approximately 130% $\text{VO}_{2\text{max}}$ performed interspersed with 4-min rest periods between each work bout of varying intensity to judge the effectiveness of passive and active recovery modalities, they reported that active recovery may delay muscle glycogen replenishment after high-intensity cycling performance.

In addition to the value of low intensity activities such as swimming and cycling for recovery, stretching is a key component of the daily training plan for athletes and plays an important role in the recovery process with the aim, ultimately, to prepare athletes for the next training session. Stretching increases blood flow to muscles, stimulates the passage of amino acids into muscles, accelerates protein synthesis in cells, and inhibits protein breakdown. Stretching as part of recovery can also reduce the chance of injury (Herman, Barton, Malliaras, & Morrissey, 2012) and increase the chances of optimal performance (Turki et al., 2011). Caution was recommended for stretching after eccentric actions (Lund, Vestergaard-Poulsen, Kanstrup, & Sejrsen, 1998) as it was reported to lead to delayed onset of muscle soreness. This conclusion by Lund et al. (1998) highlighted the greater decrease in both concentric and eccentric quadriceps strength following the use of eccentric exercise and stretching, in comparison to using eccentric exercise alone. This is an important consideration for practitioners working in rugby, where eccentric actions are commonly performed and resultant muscle soreness reported (McLellan & Lovell, 2012). Additionally, when utilising active recovery, practitioners should be cautious not to add more fatigue to the athletes in the hours post-match, by incorporating recovery sessions. The intensity of sessions should be low and a decision upon whether the active recovery session will aid restoration and recovery, or hinder it, needs to be made. Athlete compliance in the hours post-match is often difficult to guarantee as they are often emotionally and physically drained from performance, meaning that perhaps complete rest is the better option for beginning fatigue reversal.

2.5.1.5 Sports massage

Massage has been used for general relaxation of the muscular skeletal system, with sports massage directed into local areas being one of the most commonly used recovery modalities in team sport settings (Hongsuwan, Eungpinichpong, Chatchawan, & Yamauchi, 2015; Nedelec et al., 2013). Sports massage is possibly the oldest method of treating fatigued muscles and is performed on athletes to aid recovery or to treat pathology where type and duration of massage have varied considerably. Both positive effects of sports massage (Micklewright, Griffin, Gladwell, & Beneke, 2005) and negative effects (Jonhagen, Ackermann, Eriksson, Saartok, & Renstrom, 2004) are well documented, with adaptation and recovery from DOMS reported (Andersen et al., 2013). The study by Micklewright et al. (2005) reported enhanced 30 s Wingate performance as a result of massage, yet the relevance of the results to elite rugby are questionable. In a recent meta-analytical review of massage and performance involving twenty-two studies, Poppendieck et al. (2016) reported that limited positive effects of massage exist as a recovery intervention for competitive athletes. Results from the research by Poppendieck et al. (2016) showed a tendency towards more positive results amongst untrained athletes (ES = 0.23) in comparison to trained athletes (ES = 0.17), with results also favouring mixed exercise application (ES = 0.61), rather than strength (ES = 0.18) or endurance (ES = 0.12) forms, when assessed by effect sizes using Hedges' g values.

In a literature review of sports massage, muscle soreness associated with DOMS and the potential benefits of massage were noted by Moraska (2005), yet the affect that massage has upon force recovery was concluded as unclear. Change in performance as a result of sports massage is also less well reported (Robertson, Watt, & Galloway, 2004), with no measurable physiological effects of leg massage noted compared to passive recovery, post high intensity exercise (30 s cycling). Hemmings, Smith, Graydon, and Dyson (2000) reported scientific support for the use of massage to improve psychological state, yet also raise questions about the

benefit of massage for physiological restoration and repeated sports performance. By contrast, Micklewright et al. (2005) noted no improvement in mood state following massage, but did note 30 s Wingate performance was improved following massage compared to rest. Additionally, it is interesting to note the recent research by Andersen et al. (2013) showing that the positive effects of massage, which occur during the first 20 minutes after treatment, in fact diminish within an hour. The study by Andersen et al. (2013) illustrated the acute effects of massage or active exercise in relieving muscle soreness and concluded that either active warm-up or massage can be used to reduce DOMS. However, it could be argued that the eccentric contractions of the upper trapezius muscle on a Biodex dynamometer utilised in this study to assess effectiveness of massage are not of relevance to rugby research, where the whole body is exposed to ischemia and blunt force trauma. The above research into sports massage illustrates the contrasting evidence for massage as a recovery tool. Yet, if massage is a regular feature within a specific athlete's "recovery toolbox", then it best to leave this in place and monitor the resultant effect, rather than remove it from an athlete's daily routine, despite its use possibly being based upon research irrelevant to the sport in question. More research, incorporating well-designed research studies involving team sports, is needed to conclude whether or not massage facilitates recovery post rugby match play. The extent to which massage can beneficially affect a rugby player post-match may be significantly different to that of other sports considering the variations in actions performed.

2.5.1.6 Sleep to aid recovery

Sleep is considered to be a complex and physiological phenomenon that has two classified states; rapid eye movement (REM) and non-rapid eye movement (NREM), with the primary need for sleep being neural based rather than a mechanism necessary for tissue repair alone. NREM consists of four stages of progressively deeper sleep and is associated with the release of growth hormone, which is important for optimal sporting recovery. Two main methods are used to assess sleep; one being a non-invasive ACTi graph and the other being polysomnography which is considered to be the "benchmark" for assessing sleep quality and quantity. Research upon the effect of sleep deprivation in sports performance is well documented (Mejri et al., 2014; Oliver, Costa, Laing, Bilzon, & Walsh, 2009; Skein, Duffield, Edge, Short, & Mundel, 2011; Skein, Duffield, Minett, Snape, & Murphy, 2013), with the resultant effect upon post-match recovery affecting many performance measures. Sleep is considered to be the premier recovery tool for many elite athletes due to the anabolic processes that occur during periods of sleep, thereby aiding athletes to prepare and recover from training and competition demands (Halson, 2008). In a recent review of sleep and its influence upon performance, negative effects of sleep loss were associated with physiological, psychological and immune suppression (Fullagar et al., 2015). The acute response of sleep deprivation was illustrated by Killer, Svendsen, Jeukendrup, and Gleeson (2015) who noted progressive declines in sleep quality, mood state and exercise performance during a period of short-term, intensified training in elite athletes. Further evidence for the importance of quality sleep during intensive training periods was shown by Kölling et al. (2016), who noted improved recovery and stress ($p < 0.1$) following additional sleep opportunities for rowers during training camps. Results from this study showed improved subjective feelings of well-being as a result of extended sleep periods, with sleep noted as being a simple and effective strategy to enhance recovery and stress related ratings.

Research by Leeder, Glaister, Pizzoferro, Dawson, and Pedlar (2012) across multiple Olympic sports noted that the average sleep time of athletes is $8:36 \pm 0:53$ hr:min and that a sleep periods of less than this range are not recommended. When considering that travel demands, unfamiliar sleep environments and pre-competition stress can often add to an athlete's sleep disruption, the need to maximise and monitor sleep responses are, therefore, paramount. The deepest and most restorative sleep often occurs from 10pm until 2am, therefore having implications for athletes who play in night games. When evening games occur athletes are unlikely to be in their beds until 2am, due to post-match involvements such as getting showered, conducting media obligations and refuelling. In addition, perhaps the most underestimated factor affecting evening post-match sleep commencing is the inability to fall asleep after the excitement of performance. Evidence supporting this notion was presented by Eagles, McLellan, Hing, Carloss, and Lovell (2014), who noted that the time to sleep on game nights was significantly ($p < 0.05$) later than on non-game nights in professional rugby union players. This excitement post-performance, combined with ergogenic aids such as caffeine (outlined in Chapter 2.5.1.7 below), means that athletes understandably struggle to relax post-match, thereby impacting upon their post-match recovery. When considering and combining these difficult post-match relaxation logistics, including the need for athletes to travel immediately post-match (often across time zones) and compete again in a short number of days, the impact this can have upon restoration of performance in the days post-match is further emphasised.

As recommended by Halson (2014), monitoring of sleep quantity and quality as is often included within aforementioned well-being questionnaires and their results can also be useful for the monitoring of fatigue. The early detection of overtraining via the use of well-being questionnaires, however, is unclear (Halson, 2008). Within rugby specifically twenty eight male rugby union players had their sleep patterns assessed over a four game period via an *ACTi watch*, with results demonstrating that sleep was deprived post-match and that this may have had a detrimental effect upon the recovery process (Shearer, Jones, Kilduff, & Cook, 2015). Additionally, in an assessment of sleep in collision sport athletes (Swinbourne, 2015), it was reported that collision sport athletes experienced reduced sleep quality during intense training phases. However, perhaps most important from the research by Swinbourne (2015), was the finding that a sleep extension intervention elicited a significant moderate ($-0.65; \pm 0.99$) improvement in the percentage change in sleep quality scores compared to the control ($-24.8\%; \pm 54.1\%$). This notion, therefore, supports the views that the implementation of a sleep extension with rugby players is likely to be worthwhile for reducing the reported rises in cortisol levels ($-18.7\%; \pm 26.4\%$) and small ($-0.44; \pm 0.31$) resultant improvements in reaction times ($-4.3\%; \pm 3.1\%$) demonstrated by Swinbourne (2015).

2.5.1.7 Nutritional interventions to aid recovery

Rehydration during and post training or competition is the first key nutritional intervention that practitioners should focus upon to fasten a return to homeostatic balance. Fluid deficits of 2-4% are common following team sport exercise (Maughan & Shirreffs, 2010; Shirreffs & Sawka, 2011), with physiological changes noted such as changes in extracellular osmolarity that is suggested to influence glucose and leucine kinetics (Keller, Szinnai, Bilz, & Berneis, 2003). Rehydration post-session has been shown to effect subsequent sessions positively (Shirreffs, Taylor, Leiper, & Maughan, 1996), allowing adaptation and regeneration for the next session to be advanced as a result of strategies implemented in the hours post-exercise. Research into

rehydration strategies post rugby match play is lacking, although the use of a body mass urine specific gravity refractometer was recommended by Holway and Spriet (2011) in order to help identify team sport athletes prone to dehydration. An additional concern regarding hydration that practitioners should take note of, as noted by Maughan and Shirreffs (2010), is that, during competition periods, many athletes report for training in a hyper-hydrated state, which can be just as detrimental upon performance as a dehydrated state.

Alongside rehydration post exercise, foods consumed in the immediate hours post-exercise make a large contribution to the recovery process, with restoration of muscle glycogen reportedly remaining attenuated for 2-3 days (Nedelec et al., 2012, 2013). Adequate muscle glycogen replenishment and a healthy diet will aid individuals in recovery during periods of excessive training, speeding tissue repair and promoting adaptations to training. In a review of nutritional strategies to maximise performance in rugby Casiero (2013) recommended intake of appropriate nutritional refuelling in the hours post-exercise in order to enhance recovery. Repair and re-synthesis of muscle cells is key, with the size of the snack or meal depending upon the type, length and intensity of the exercise undertaken. Specific guidelines regarding when and what to eat post team sports vary (Mujika & Burke, 2010), with an athlete's overall nutritional aims guiding their refuelling process post-exercise. The need to refuel is always of importance, although calorie restriction should also be considered within other time-periods of an athlete's day, rather than in the immediate hours post-exercise. Effective nutritional recovery maintains energy and limits tissue breakdown, especially during periods of high volume/high intensity training, with both carbohydrate and protein being essential to the plan (Macnaughton et al., 2016). One of the key factors to keep in mind is that the "window of opportunity" for maximising glycogen repletion starts to close as soon as exercise stops and lasts for about up to four hours (Mujika & Burke, 2010).

Carbohydrates are probably the most researched form of recovery strategy post-exercise, with the utilisation of carbohydrate during exercise being recommended for sustained performance (Jentjens & Jeukendrup, 2003). This review by Jentjens and Jeukendrup (2003), however, outlines the use of food sources post-exercise to enhance recovery, with team sport activities reported to deplete fuel sources during competition (Costill et al., 1973). Carbohydrate forms the majority of food intake post-exercise, with food sources with a high or moderate glycaemic index (GI) recommended for rapid replenishment of glycogen stores in the liver and muscle. Since carbohydrates are the primary source of energy in training and competition, it is important that these losses are replaced before the next exertion. Research, reporting that during a soccer match muscle glycogen stores usually deplete by up to 75% during a match (Bangso, 2000), also provides guidelines for carbohydrate intake post-game as being 1-1.2 g per kg of body mass. As mentioned previously, more recent research (Bradley et al., 2016) into rugby league has subsequently reviewed muscle glycogen stores and fatigue research, with glycogen pools noted to affect muscle contractility and fatigability. In relation to carbohydrate replenishment post-match play, perhaps most interesting from the research by Bradley et al. (2016), is that rugby league players were noted to use < 40% of their glycogen during a competitive match regardless of their carbohydrate consumption in the preceding 36 hours. This evidence by Bradley et al. (2016) does not dispute the importance of carbohydrates during and after exercise, but it does present a point for consideration for practitioners when using nutritional interventions to hasten recovery and restoration post rugby match play.

Research assessing the influence of resistance training and timing of protein ingestion is also well documented (Tipton et al., 2001), yet the influence of protein post-rugby is unclear. Protein intake with carbohydrates is recommended especially after hard training such as weights, sprinting or when impact activities have been undertaken (Howarth et al., 2009; Minett et al., 2010; Moore et al., 2009). Protein is especially important for muscle regeneration and the prevention of exercise-related anaemia and is therefore a commonly used food source for many rugby players (Casiero, 2013). Rugby players are advised to include some protein alongside their complex carbohydrates within their post-exercise meal. A ratio of 4:1 is a good recommendation, with guidelines for protein intake post-game being 0.3 - 0.4 g per kg of body mass (Casiero, 2013).

Within team sport settings where activities differ from resistance training, active recovery sessions and “on field” team activities, the guidelines for post-activity nutrition may vary. The nature of individual training days within the team sport setting may guide the food and fluid intake. For example, a player may fuel differently after an intense training day compared to a light training day, typically the day prior to a game. One aspect that should remain constant throughout, though, is that food and fluid replenishment should be an integral part of the team’s recovery strategy after games. Within elite sport, supplements have become a regular addition to an athlete’s post exercise nutrition strategy. Although a well-balanced diet is considered appropriate for optimal recovery, many rugby players use supplements for logistical purposes and to add calories to a daily diet where they are considered necessary during periods of intense training, or periods when added lean muscle mass is the goal of the training strategy (Roberts et al., 2011). Many supplements are now included within an athlete’s daily routine, including the use of dietary nitrates (Jones, 2014) and tart cherry juice (Bell, Walshe, Davison, Stevenson, & Howatson, 2015) both of which have received significant praise for their use due to their ability to increase antioxidative capacity and enhance recovery (Howatson et al., 2010). Foods and fluids are, however, considered to be a preferred option to supplements, as they contain many nutrients that supplements cannot supply thus encouraging a more balanced routine within an athlete’s daily life.

An additional point to consider for practitioners regarding food and fluid intake in the immediate hours post-game is alcohol. In a study assessing alcohol use within rugby union in New Zealand, Quarrie, Feehan, et al. (1996) noted patterns of the sample group’s alcohol use as being of concern and emphasised their potential impact upon performance. The effect of alcohol during recovery periods post-exercise has been shown to be detrimental (Barnes, 2014), with the consumption of 1 g of alcohol per kg of body mass negatively affecting lower body power output post simulated rugby match (Barnes, Mundel, & Stannard, 2012). Within rugby league alcohol was also noted to have detrimental effects upon peak power, measured via CMJ and cognitive function (modified Stroop test) in the hours post-game (Murphy, Snape, Minett, Skein, & Duffield, 2013). This thesis, however, focuses more upon the NMF elements of restoration of performance, rather than the lack of macronutrient supplementation post-exercise to restore performance.

2.5.1.8 Rest and days without training

Perhaps the most under researched and least strategically implemented strategy to enhance recovery post-exercise is rest days. Despite rest being the most obvious strategy to implement post-exertion in order to manage fatigue, it could be argued that few practitioners deliberately

put rest into their periodised training plans and instead react to the response created from training. Of the limited research that does exist regarding recommended rest days for athletes, Bruin, Kuipers, Keizer, and Vander Vusse (1994) in a study of adaptation and overtraining in horses, reported that the absence of a recovery day was related to the onset of signs of overreaching and under recovery. Replenishment of substrates and the repair of muscle damage induced by training and competition are the most likely reason for rest day implementation in elite rugby union settings. Without the addition of rest days to enable the replenishment of substrates and the repair of muscle damage, rugby players are likely to produce sub-optimal performance. When considering research that reported time-course of restoration and substrate decrement (Bradley et al., 2016; Casiero, 2013; Cunniffe et al., 2009; Lindsay, Lewis, Scarrott, Gill, et al., 2015; Minett et al., 2010), the implementation of rest days where fatigue is dissipated is therefore potentially more advantageous than days that involve training.

It is also important for practitioners to understand that rest days are not solely put in place for physical recovery but also with the aim of positively impacting mental recovery. Days without training provide athletes with a distraction from the daily routine of training and in addition will reduce perception of mental fatigue due to time away from organised training events. It could be argued that psychological recovery achieved via rest days is just as important as physiological recovery. When considering that physiological stress is difficult to identify and variant in mechanism, perhaps the attention of practitioners should, instead focus upon investigating psychological recovery alongside physiological elements as recommended by Rattray et al. (2015). Despite limited research existing as regards psychological stress post-exercise, psychological stress is, perhaps, a more easily investigated area in comparison to physiological stress and therefore warrants attention.

Alongside physiological stress, rugby union match play demands high levels of cognitive activity and most likely will have a cost upon subsequent recovery. The neurological fatigue created from exertion can be reduced by the implementation of rest days from training, which, if planned appropriately, will have a positive influence upon adaptation. It is, however, important for practitioners to note that some physiological focused recovery interventions (massage, for example) also potentially encompass a psychological restorative element (Poppendieck et al., 2016), whereby the individual perceives care and consideration for their current physiological and psychological state to be present. The same notion can perhaps be said for active recovery sessions (swim recovery, for example). The likelihood, however, of this being true for modalities such as CWI immersion (which typically carry less compliance) can be questioned. It is important that practitioners note the potential negative psychological influence that a recovery intervention might have, even if this modality has been deliberately implemented into an athletes training schedule alongside a pre-planned rest day. If a modality such as CWI is not enjoyed, or not perceived as beneficial by individuals, this could be having a negative effect upon the global recovery response, when considering the influence of the added psychological stress. In summary, the ability of practitioners to implement rest days, at the appropriate time and for the appropriate number of days, is mainly due to common sense and “coaching art”. Experienced coaches will likely recognise periods of fatigue using some of the objective training load management methods (GPS and HR) and subjective measures (WB) of assessment outlined in Chapter 2.4. Coaches are, however, advised to use their coaching experience and their

knowledge of the individuals they oversee to implement rest day interventions where appropriate.

2.5.1.9 Selecting the appropriate recovery modality

As proposed in research from Yamane et al. (2006) the micro damage, cellular and humoral events induced by endurance and strength training are important aspects of the adaptive process which lead to improved performance. This adaptive process is, therefore, contrary to the application of recovery modalities that hasten the recovery process. Recovery interventions go beyond the natural mechanisms involved within the physiological training adaptation process and as reported above are regularly implemented. From the evidence presented above, it is clear that “recovery training” in team sports is an aspect of importance. Selecting the appropriate recovery modality is, therefore, a key decision for practitioners and is dependent upon many factors, including the recognition that what has fatigued the athlete, is of prime importance. Not only do the mechanical movements performed affect the response created but the nature of the movements also affects the fatigue outcome. For example, if metabolic fatigue is created then perhaps replenishment of fluid and fuel stores need to be administered, whereas if the movement involved explosive exercises, then the fatigue may be more psychological in nature and therefore another recovery intervention may be better suited. Regardless of the fatigue mechanism created, enhanced recovery following completion of an athletic task is crucial for future performance for many athletes, although reliable and specific scientific evidence to support recovery strategies has yet to be found. It is, however, important for practitioners to note that the poor evidence to date for assessing the recovery strategies post exercise exertion, is partially the result of; a lack of diagnostic tools available to assess effectiveness, large variability of results of research studies and a lack of well controlled studies.

Individualisation of recovery strategies by practitioners is recommended due to the individual nature of recovery post contact sports (position-specific) and the requirement to monitor the individual responses to interventions required to assess effectiveness. Another consideration within team sport settings is availability of resources, with a pragmatic approach often considered best when choosing the intervention to implement. Within team sports the number of athletes to recover is large, meaning that logistical considerations and time constraints are of importance. The cost of selected modalities has impacted upon commonly used practices in team sports, with techniques which can be self-administered and incur no cost often being the modalities most readily used. Sustainability and manageability are considered important for athlete compliance, as recommended by Cook, Kilduff, and Jones (2014), with sleep and nutrition being identified as the two most critical elements of the recovery process. Despite many practitioners hoping to use expensive and cutting edge technologies within their recovery process, budget restrictions often limit the use of modalities such as WBC, which incur a greater time and financial investment. A holistic approach to a rugby players daily and weekly schedule should be used so that physical stress, psychological stresses and off-field demands are managed.

Within the professional team sport environment it is not solely the coaches’ responsibility to manage the recovery process. The ability of practitioners to make athletes accountable and self-aware within their training and recovery process will increase compliance and subsequent recovery. If athletes, however, are not compliant or do not listen to their bodies throughout a

competitive season they will struggle to cope with the workload and maladaptation could potentially occur.

2.5.2 Summary

Contrasting evidence supporting the effectiveness of many recovery modalities exists, mainly due to the methodology used, protocol undertaken and performance measures assessed being so varied in nature that no clear agreement can be concluded. The need to research recovery practices in rugby union is therefore of importance to practitioners aiming to improve player readiness between games, where supposed benefits need to be considered against the financial and practical implications that each modality assumes. Modalities that provide simplicity of administration and low financial cost, will most likely be the intervention strategy implemented within many elite rugby settings. A sound recovery theory with consistency of administration and player education embedded into daily lifestyle choices such as sleep and nutrition, is considered an effective starting point for enhancing rates of recovery post rugby union match play and to improve player compliance. The choices of additional recovery modalities being used by elite clubs, alongside improved lifestyle choices to enhance recovery, are likely to be scenario specific. It is, however, important for practitioners to note that management of fatigue does not always require the use of recovery modalities and that instead coaches should look to manage fatigue by monitoring readiness (using methods outlined in Chapter 2.4), alongside controlling the variables that they have the power to manipulate (intensity, volume and rest days).

2.6 Relevance of readiness and restoration research

As was recommended by Pyne and Martin (2011), a systems based approach that integrates well-chosen diagnostic tools is considered to be the future for fatigue management in elite sport. The above diagnostic tools and recovery modalities need to be selected based upon the movements and activities of the sport and the fatigue response created. As a result of using a system-based approach that encompasses recovery and restoration of performance monitoring, overall player readiness can be better assessed. The increasing amount of commercially available athlete monitoring systems in elite rugby (*RugbySquad*, *Egde10*, *Apollo* and *KitMan Labs*) make integration of performance monitoring data within the athlete's training regime more easily accessible and enable better management and reporting. It is important to note, however, that data collected within an elite rugby setting should not be used solely for research purposes and should instead be prioritised for use to improve rugby players' daily training and playing readiness.

2.6.1 The importance of readiness

NMF is perhaps a term that could be perceived as having a negative connotation by sports coaches. Therefore, sports science practitioners should perhaps use the term "neuromuscular readiness", as this is less likely to be construed as a performance test that can only detect fatigue in a negative context. Instead, readiness assessment will aid sport specific coaches to understand the mechanism and causes of the fatigue and guide practitioners in choosing a specific readiness assessment tool for the sport in question. The term "readiness" has been used in various recent studies, ranging from Plews, Laursen, Stanley, et al. (2013) mentioning readiness when using HRV and training response; Gaviglio and Cook (2014) using testosterone and cortisol to measure readiness leading up to games in rugby union; Duffield et al. (2008) when measuring the effects of compression garments and Myer, Paterno, Ford, and Hewett (2008) using "readiness" terminology when discussing return to participation criteria post anterior cruciate ligament injury. Readiness has been described as "the current functional state of an athlete that determines the ability of an individual to effectively achieve their performance potential" (Fomin and Nasedkin, 2013, p. 5). It could be argued that readiness in-season relates to restoration of performance values and that during pre-season readiness relates to the aforementioned FOR theory. High training volumes during elite rugby union pre-season periods are designed to cause a positive player adaptation to a training dose stimulus and will therefore have a differing impact upon readiness than a typical in-season tapered training week as a game day approaches. Based upon the concept of readiness, recent technological developments have enabled objective feedback on changes taking place as a result of training and competition exposure, meaning evaluation of player readiness has become more quantifiable (Fomin, Grainger, Nasedkin, Bork, & Huttunen, 2015). One could argue that the goal of every coach should be to improve the management of the functional state of an athlete, with the most important marker of this being readiness to train and play. Readiness is, therefore, the result of many different stimuli applied to the athlete from both training and non-training stressors, and is an accurate indicator of an athlete's ability to realise their performance potential, when considering cardiac pulmonary readiness, autonomic nervous system readiness and readiness of the neuromuscular system. Reduced readiness when assessed via accurate measures should provide coaches with cues to alter training load, as a result of the adaptive responses of the athlete's organism to the stimuli applied.

Readiness to train, from a sports coach's perspective, surrounds the influence of training program design and management and the impact this has upon athlete fatigue. As illustrated in Figure 2.2, many coaches follow the overloading training stimulus response (supercompensation model) for training adaptation, where an athlete is exposed to an overloading training stimulus that causes fatigue, with the body then reorganising its capacities so that the next exposure to the same stimulus causes less strain. The displacement in homeostasis caused by the overload will result in adaptation, with the recovery time between exposures being long enough for the next training stimulus to create a further positive adaptation from homeostasis. The accumulation of training effect and possible training stress, where the recovery periods between exertions are not sufficient, will result in inadequate adaptation. Monitoring of an individual athlete's responses to the training effect imposed is therefore of significant importance, in order to avoid maladaptation and improve daily readiness to handling training exposures.

Readiness assessment by practitioners can result in the load being applied at an appropriate time within the training process. This utilisation of "windows of trainability" enables coaches to prescribe specific sessions with the appropriate load, with the aim of producing optimal performance. In essence, readiness assessment enables coaches to manage athlete preparation based upon readiness measures, which assess NMF and the athletes' overall functional state. It is common practice for coaches to design long-term training programs, without taking into account the response of the athlete to the load implemented. Readiness assessment could be considered to be a more athlete-focused approach to optimal training than the more commonly used training-focused process. Concurrent alterations to a long-term periodised plan using readiness assessment increases the chances of optimal performance, while avoiding maladaptation or potential injury.

2.6.2 Meaningful change

Coaches want to know that their athletes have recovered from training or game exertion. Often, though, players will not have recovered completely from training and games, yet have to compete again. This insufficient recovery, prior to commencing another training session or game, is common in many team sport environments where time between games is limited and the need to prepare for and compete within the next game are essential. Practitioners need to ascertain whether they should be looking for faults in player performance through testing, or be alert to clues that should be investigated further to assess readiness. One could argue that readiness does not mean complete restoration of performance to pre-game levels, as often this is unrealistic in rugby where the number of days between games are small. This lack of restoration of performance to pre-game levels does not mean, however, that optimal performance cannot be attained, and should, perhaps, not be considered too much of a concern in the elite setting.

Incomplete recovery is therefore a scenario that should be considered when preparing athletes, although it that should not cause too much concern. A more specific concern should be the level of performance decrement, rather than that there is a decrement in the first place. As mentioned in Chapter 2.3.6, performance decrement is commonly seen, especially in the later periods of playing seasons when cumulative fatigue is a factor. The ability to identify decrement in performance and associated readiness is only one task for strength and conditioning coaches. The decision over when to act upon this change and implement intervention for the player in question is the key area of future focus in readiness to train. As supported by Twist and Highton

(2013), more research needs to be conducted to understand more clearly what meaningful change represents, for selected monitoring tools, before any interventions are made. More informed decisions could be made upon readiness when knowledge of performance standards in the tests critiqued above is combined with a coach's instinctive understanding of their players. This combination of objective and subjective measures was recommended by Twist and Highton (2013), who identified that large changes in performance, combined with an increase in perceptual fatigue, could aid coaches in making decisions upon readiness using assessments such as CMJ, HRV and self-report well-being.

The importance of individualised monitoring is key, with research by Pyne and Martin (2011) illustrating the need for a system-based approach that integrates well-chosen diagnostic tests. It could be argued that one athlete's readiness data cannot be compared to another, as reaction to the training dose-response relationship is bespoke to the individual. Individual rugby players are expected to have differing capabilities to adapt to the same training load, with the physiological and psychological buffer zones determining the resultant fatigue response. As reported by Twist and Highton (2013), the multifaceted elements of fatigue and the physical and mental response that individuals athletes demonstrate, mean that single biochemical, hormonal or performance tests do not present a clear picture of athlete readiness, but instead mean that athletes should be monitored within a multi-method individualised approach. Additionally, Twist and Highton (2013) discourage the use of arbitrary cut-off points across measurement tools when alterations in performance are reported. Previous research has investigated inter-day reliability of measure for each individual, by assessing repeated measures. Twist and Highton (2013), when assessing change, reported multiplying factors of 0.3, 0.9 and 1.6 to determine what would be small, moderate and large changes, while Hopkins (2004) proposed the implementation of SWC values within performance testing, in order to determine whether or not a meaningful change has occurred. A meaningful change was noted to occur when CV error bars lay outside of the SWC threshold, with this method proposed, therefore, for use by practitioners in assessing readiness to train.

The collection of average scores for individuals, on selected performance measures assessing fatigue post periods of rest or perceived optimal state, is key. The aim for practitioners is to establish a stable value for each individual that can be used to serve as a comparison as the season progresses. It could be argued that the most important comparison is intra-individual, yet it is recommended that practitioners pay specific attention to the comparison of acute and chronic training alongside individual fatigue responses as recommended by Hulin, Gabbett, Lawson, Caputi, and Sampson (2016). The ability of practitioners to be able to make informed decisions based upon fatigue data (irrespective of the testing variable used), while also considering the acute and chronic training response will take a large amount of data collection and analysis. However, if reliability values (CV%) and SDD are detected prior to collation of data, this will be of benefit for informed decision-making moving forward. This notion of individualised monitoring within rugby union was further supplemented with the recent application of bespoke high speed running values by Reardon, Tobin, and Delahunt (2015). Reardon et al. (2015) recommended the use of positional sub-categories when interpreting high speed running demands, to enable making more informed decisions on the data collected.

2.6.3 Improving readiness

If practitioners are confident in making informed decisions based upon readiness of their athletes to perform, improved performance and reduced presence of injury from training and competition seem likely to occur. This assumption could be made for many sports where coaches are often unsure of the appropriate training dose needed. In addition to practitioners being able to make informed decisions over whether or not athletes should train, perhaps the area that elite practitioners should be focusing upon is the need to improve readiness, if required, and how best to do so. Specific recovery protocols and adjustable training schedules on the day post-performance are of significant importance. Athlete involvement and feedback in the monitoring process are valuable, as the empowerment and sense of ownership given to the players will enhance the process.

The ability to quantify decrement in key performance indicators and associated readiness, or neuromuscular function from a functional test such as jump height, is a key area of focus for future research, especially during periods of intense training or playing. Considering the research by Gabbett and Jenkins (2011), who noted a relationship between athlete fatigue and injury rates in professional rugby league, pre-season periods (when player load is high) are potentially of most significance. Increased training loads and incidence of injury were studied by Killen et al. (2010), with no significant relationship observed in professional rugby league, yet the pre-season period was signified as a key time for injury to occur. Despite injury and training load being interlinked and therefore being of importance to practitioners, the area of focus for this research does not include injury. Injury's relationship to readiness, however, could be considered as a future area of study for return to play protocol. In an analysis of return to play (RTP) protocol post-injury by Reid et al. (2013) in elite level rugby union, a progressive rugby-specific training program was recommended based on a player's positional demands. Due to the frequency, intensity, and duration of running efforts by each playing position being vastly different during games, as detailed in Chapter 2.1, position-specific training programs involving RTP protocol are common practice (Reid et al., 2013). The use of GPS data in conjunction with fatigue monitoring measures, as discussed in Chapter 2.1.2, will provide practitioners with more informed decisions throughout the rehabilitation period post-injury.

Twist and Highton (2013) noted that performance test data assessing neuromuscular function, combined with perceptual data from questionnaires, would provide a more accurate understanding of player fatigue. This notion is further endorsed by more recent research assessing measurement sensitivity of monitoring tools (Crowcroft, McCleave, Slattery, & Coutts, 2016). As previously discussed, Twist and Highton (2013) noted the multifaceted elements of fatigue and the physical and mental response that individual athletes demonstrate, with a multi-method approach that assesses any change below baseline recommended for implementation. Practitioners using jump testing to assess NMF, for example, should question at what percentage jump performance reduction warrants altered training volume or intensity. Below baseline change plus the ability to have objective measures of readiness to train are therefore paramount, so that a player knows when to return to full training instead of holding back based upon the reported altered sense of fatigue (McLellan et al., 2011b; Sykes, Nicholas, Lamb, & Twist, 2013). Considering that players often resume resistance training in the immediate days after a match and often before any field sessions, the views of Jennings, Viljoen, Durandt, and Lambert (2005) are of note. Jennings et al. (2005) indicate that resistance sessions could perhaps provide the opportunity for coaches to monitor power output during exercises such as

bench press, prior to the main training session commencing later in the day. Gymnasium based sessions on the morning of a training day are common within both rugby league and rugby union, enabling practitioners to assess players readiness to train in subsequent sessions that day. During the early part of their training day (in the gymnasium), decisions could be made based upon the results of the mornings readiness testing, thus providing better overall management of daily player training prescription.

2.6.4 Limitations of the research to date

Equipment available for use in assessing performance measures and the time available to perform the testing were also limiting factors within this research. Although force plates would have provided more detailed analysis of player performance when assessing CMJ, the logistical and financial involvement of force plate testing made this unrealistic. Additionally, the short periods of time available on a typical training day to collect performance measures meant that often fewer individuals than desired were assessed on a daily basis. This smaller sample size collected, therefore, presented a less detailed analysis of performance across the whole rugby playing squad, yet the time constraints involved are considered to be a “real world” scenario within elite rugby union testing, where players’ and practitioners’ time is limited within busy training days in the lead up to competitive games.

Another limitation of this research exists within the game data collected where, although this research assessed the demands of player actions during game situations, it did not consider the effect impacts (measured via GPS) from contact situations had upon players, as was researched by McLellan and Lovell (2012) during rugby league match play. When assessing neuromuscular responses to impact and collisions during elite rugby league match play McLellan and Lovell (2012) reported impacts > 7G as being a significant influence upon neuromuscular fatigue. This research by McLellan and Lovell (2012) does not include the movement classification of impacts experienced and instead simply focuses upon the volume of impacts. This lack of detail surrounding the magnitude of impacts experienced is an obvious limitation in this research and one that would be amended in future study to guide practitioners more clearly on the typical restoration of performance timings for positional groups.

Lastly, a limitation of this research also surrounds rugby coaches making decisions on when to train and when to rest, with no consideration for the evidence collected. Although, in this respect, guidance can be given to sport specific coaches from sports science practitioners, the rugby coaches and not the sports science practitioners often make the final decision. This notion, that sport specific coaches have the power to overrule sports science practitioners and medical personnel, upon when to train and when to rest, is a commonly reported issue in elite rugby. Although this notion of the rugby coaches making ill-informed decisions upon individual player training availability is not ideal for best practice, this process of player management is simple a “real world consequence” of elite sport, where the pressures to succeed are high and the emphasis to push players when perhaps ill advised is a commonly seen phenomenon. Decisions regarding weekly training structure, and consequently individual player management, are often guided by external factors such as weather and instinctive “coaching art”, rather than being driven by scientific data aimed at enhancing performance, while incorporating restoration of performance measures and associated readiness. Based on these findings it is the author’s belief that “coaching art” and “performance science”, delivered by practitioners to rugby coaches, while keeping in mind logistical issues regarding player management, would be the best combination to for achieving optimal results.

2.7 Summary of research proposed

In summary, the above literature review has led to the conclusion that readiness testing, assessing restoration of performance levels, is essential within elite rugby union settings. Although, implementing performance tests that fit well within a team's daily and weekly structure, that would benefit decision making over player preparedness, is more problematic. The overall aim of the following research chapters is, therefore, to identify a monitoring tool that could effectively assess restoration of performance post rugby union match play.

Firstly, a specific objective of this research was to ascertain the match demands experienced by elite rugby union players. Via analysis of match data taken GPS, assessing movement requirements, match load experienced by players will be revealed. As previously stated, the novel aspect of this research in comparison to that of previous study (Cahill et al., 2013; Quarrie et al., 2013), is that this research encompasses players who play less than 80 minutes of a rugby match and thereby represent a true reflection of current elite positional demands. Secondly, another objective of this research associated with the collection of match demands data, encompasses assessment of performance tests that identify the match characteristics that affect time-course of restoration. Although this research will not assess which match characteristics influence restoration of performance to a greater degree than others, an understanding of the sensitivity of selected performance tests will be ascertained. Match characteristics that impose a greater levels of fatigue with resultant longer periods of restoration of performance are of significant interest to the rugby clubs and could help them plan subsequent training sessions post-game, for both positional groups and individuals.

In addition to assessment of GPS match data; a further objective of this research was to identify a measurement tool that would assess restoration of performance and readiness for training and match play within rugby union. This measurement tool has to be accurate, reliable and feasible for use within elite rugby environments, where time and budget constraints exist. The tools proposed for assessment of readiness are, therefore, the CMJ test and the self-report well-being questionnaire. These tools are used to assess pre and post-match changes in performance, with restoration of neuromuscular function collated via CMJ performance tests, and the more subjective notions of recovery collected via self-report well-being questionnaires. CMJ and WB questionnaires were identified for use from the literature review above; due to the ease with which they can be implemented and the logistical issues that surround the setting in question. Previous match characteristic research and the effect that matches have upon restoration of performance have predominately focused upon rugby league (Johnston et al., 2013; McLellan et al., 2011b; Twist & Highton, 2013; Twist et al., 2017; Twist et al., 2012), with limited research into rugby union specifically (Crewther et al., 2009; West et al., 2014). This research aims to add to the knowledge of performance measures that can detect a meaningful change in neuromuscular function as a result of specific match characteristics in rugby union.

Lastly, another objective of this research was to assess the frequency and magnitude of impacts experienced by players during elite rugby union match play, using both video footage and GPS data. This combination of methodologies will provide practitioners with greater insight into elite rugby union impacts, as the footage and GPS data combined will provide more detail than earlier research (Cahill et al., 2013; Coughlan et al., 2011; Venter, Opperman, & Opperman, 2011). The studies by Cunniffe et al. (2009) and Cahill et al. (2013) did not involve analysis of impacts, while two studies that do consider impacts within match analysis assessment

(Coughlan et al., 2011; Venter et al., 2011) involve smaller sample sizes and less extensive analysis of impact across positional groups. A more detailed analysis of where impacts occur during match play will further help quantify the demands experienced by players and will provide additional information about the effect of specific match characteristics upon time-course of recovery for positional groups. The GPS data collected within this study will identify the match intensity experienced by the players (illustrated by GPS variables), while the video footage will act as a reference file against which to compare the GPS results data. This combined data collection will help to ascertain match involvements and their associated impacts.

The novel approach outlined within this research, incorporating greater analysis of match data and more specific use of the methods of neuromuscular assessment presented in Table 2.13, will enable a more global overview of player readiness. This is in contrast to research by McLean et al. (2010) and McLellan et al. (2011b) who only used CMJ, biochemical and WB values and did not provide any immediate feedback to players or practitioners, with the result that concurrent interventions could not be implemented. To date, methods used in the key research by McLellan et al. (2011b) included questionable CMJ protocols where, for example, subjects hands were not placed upon hips during the jump. This protocol has been shown to be inaccurate (Domire & Challis, 2007) where arm swing allows greater muscular force to be generated, therefore illustrating that some of the results presented may be difficult to compare.

2.7.1 Research questions proposed

- Do the physiological requirements of elite rugby union players differ across positional groups, irrespective of duration played?
 - Do backs cover a greater distance across all distance zones compared to forwards?
 - Are forwards involved in a greater number of impacts across all impact zones compared to backs?
 - Are backs involved in more accelerations and decelerations compared to forwards?
 - Do backs complete game activities at a greater intensity than forwards?
- Which jump modality is more reliable within and between sessions in elite rugby settings?
 - Are bilateral jumps more reliable than unilateral jumps?
 - Is CMJ measurement an accurate, reliable and feasible task for use within elite rugby, to assess restoration of performance?
- Does time-course of recovery of elite rugby union players post-match differ across positional groups?
 - Are CMJ performances and WB scores restored within 60 hours post-match?
 - Do forwards take longer to restore CMJ performance and WB scores due to the greater number of impacts they experience during games?
 - Do many of the impacts experienced from players during match play occur only during collision situations?

3 Match Characteristics in an Elite Rugby Union Playing Season

3.1 Abstract

An understanding of the physical demands placed upon elite rugby players during match play is important, in order for practitioners to prescribe appropriate training plans for positional groups. The purpose of this study was to quantify the match characteristics of elite rugby union players across a competitive playing season and to identify whether position-related differences exist. Thirty-eight players from one English Premiership Club were tracked using GPS during thirty-two games played throughout the 2014/2015 playing season (462 data sets). This study involved nine positional groups, which were defined as: backs (n=220) or forwards (n=242); and further subdivided into props (n=62), hookers (n=30), locks (n=59), back rows (n=95), scrum half (n=34), out half (n=33), centres (n=59), wings (n=62) and full backs (n=27). The match characteristics revealed a significantly greater ($p < 0.001$) distance covered for backs (5918 ± 1206 m) compared to forwards (5035 ± 1157 m), in conjunction with the backs playing at a significantly higher intensity (70.9 ± 7.4 m/min) compared to the forwards (64.0 ± 6.3 m/min) ($p < 0.001$). Additionally, backs conducted a significantly greater ($p < 0.001$) number of accelerations (32.2 ± 10.6) compared to forwards (22.0 ± 11.9) and a significantly greater ($p < 0.001$) number of decelerations (41.9 ± 12.3) compared to the forwards (30.8 ± 14.4), while forwards experienced a greater, yet insignificant ($p > 0.05$) number of impacts > Zone 3 (229 ± 160) compared to the backs (226 ± 151). Within the nine positional groups, many differences in match demands were identified, with full backs covering the greatest distance (6904 ± 740 m) compared to the lowest being props (4285 ± 893 m) ($p < 0.001$). Centres performed the highest distance covered in D1 (2405 ± 256 m), full backs the furthest in D2 (2078 ± 275 m) and D5 (429 ± 118 m), scrum half's the furthest distance covered in D4 (1009 ± 214 m), while wingers presented the furthest distance covered in D6 (139 ± 72 m). Impact zones for the nine positional groups showed that props typically experienced the lowest number of impacts in the lower impact zones (Im1, Im2 and Im3), yet experienced a large number of impacts in the higher impacts zones (Im4, Im5 and Im6). Full backs showed a large level of impacts on both low and high impact zones, yet the positions of prop, hooker and back row illustrated high Im6 values when compared to the values they experienced at the lower impact zones. Results from this study help guide coaches upon what each positional group should complete within the team's playing structure and enable coaches to make more informed decisions upon whether an individual player can perform such a role for the team. Specific training recommendations resulting from this study are, firstly, that high levels of aerobic fitness are required to complete match distances, and secondly that high muscle mass and strength are needed to cope with match impacts experienced. Finally, implementation of match characteristic comparison could help guide the future of strength and conditioning training prescription in order to improve individual readiness to train in the days post-match.

3.2 Introduction

Rugby union, like many other team sports, is a sport of intermittent periods of both high and low intensity activity, with many gait changes during game phases (Austin et al., 2011a; Quarrie et al., 2013). The ability to identify and understand the specific demands placed upon sport performers during match-play has long since been recognised as a crucial factor in developing

appropriate training and recovery programmes, which might elicit improved performance (Coughlan et al., 2011; Quarrie et al., 2013; Roberts et al., 2008). Increased commercial interest in rugby union, since it became professional in 1995, has resulted in matches reported as becoming faster, containing more phases as well as involving bigger, faster, more physical players (Quarrie et al., 2013). Additionally, the development of GPS technology is providing practitioners with detailed data relating to the specific movement demands and work rates of players. A competitive game of rugby union lasts for approximately 90 minutes and involves high intensity activities including blunt force impact (forwards ≤ 838 impacts; backs ≤ 573 impacts) and sprinting (>24 km/h; forwards 60 ± 32 m, backs 143 ± 67 m, backs) (Austin et al., 2011a; Cahill et al., 2013; Coughlan et al., 2011; Deutsch, Kearney, & Rehrer, 2007).

Data from a recent study from the English Premiership rugby union league (Cahill et al., 2013) reported that match distances per game, averaged across a season, were significantly lower for forwards (5850 ± 1101 m) compared to backs (6545 ± 1055 m), with high intensity bouts (sprinting, tackling, static holds and scrummaging) (Austin et al., 2011a) and high impact forces ($> 10G$) (Venter et al., 2011) being a major source of cumulative fatigue throughout a game. In a recent time-motion analysis study by Quarrie et al. (2013) involving 763 players, it was clear that varying demands are placed upon differing positions (forwards 5040 ± 874 m; backs 5800 ± 822 m). The distances covered by positional groups at varying speed intensities was the key finding, implying that differing conditioning and recovery programs should be implemented to prepare players most effectively (forwards 44 ± 32 times > 8 m/s; backs 104 ± 54 times > 8 m/s). Roberts et al. (2008) found players to cover distances of 5408 – 6190 m on average depending on the positional role, with backs generally covering the greater distances, made up of sprinting, jumping and change of direction at various velocities. In a study involving 2008 and 2009 Super 14 rugby union games, Austin et al. (2011a), reported that the maximum distance covered in a game by four positional groups were: front row forwards (4662 ± 659 m), back row forwards (5262 ± 131 m), inside backs (6095 ± 213 m) and outside backs (4774 ± 1017 m). An additional study that warrants attention is that by Venter et al. (2011) which showed conflicting data. Venter et al. (2011) noted that players on average covered a total distance of 4469 ± 292 m, with front row forwards covering the greatest total distance 4672 ± 215 , followed by outside backs 4597 ± 210 m, inside backs 4307 ± 214 m and then back row forwards 4302 ± 529 m. It is, however, difficult for comparisons to be made with the research by Venter et al. (2011), as it involved a small sample size ($n = 23$) of semi-professional under 19 players, who play for 60 minutes rather than 80 minutes. Player positions, their roles and the physical characteristics associated with each position within rugby union are detailed within Table 2.1 and Table 2.11 (Chapter 2.1) of the literature review.

Reported work to rest ratios, of between 1:4 and 1:6 for varying positions exist, with the average number of sprints during a match being twenty (Roberts et al., 2008). Austin et al. (2011a) also reported work to rest ratios of between 1:4 and 1:6 for varying positions, with back row forwards spending the greatest amount of time in high intensity exercise. It is, however, important for practitioners to note that these work to rest and sprint values do not reflect the actual movement patterns during intense periods of matches (including repeated high intensity efforts) and are, therefore, only average values across the game. As reported in recent rugby league literature (Gabbett, 2013), preparing for the “worst case scenario” (work to rest ratio 3:1) is recommended, instead of the “average” reported measures of game demands (work to rest ratio 1:5), with positional differences surrounding this notion noted by Reardon,

Tobin, Tierney, and Delahunt (2017). Additionally, it is important for practitioners to note that the research by Quarrie et al. (2013) was taken from time-motion analysis assessments and not from GPS data. The difference in match demand intensity between positional groups was further emphasised in recent research by Cunningham et al. (2016) who noted that forwards (5370 m) covered less distance than backs (6230 m) and typically performed these at lower speeds (Forwards HSR 284 m; Backs HSR 656 m). Despite the research by Cunningham et al. (2016) being collated upon age grade (under 20) internationals and therefore ill-advised for comparison against studies using senior professionals, it is of interest for practitioners to note that forwards experienced greater contact loads than backs. However, the assessment of contact loads within the research by Cunningham et al. (2016) does not incorporate GPS measurements for impacts and therefore can be questioned. Instead the research by Cunningham et al. (2016) utilised earlier research (Cahill et al., 2013; Docherty et al., 1988; Quarrie & Wilson, 2000), to explain its view that forwards experienced greater contact loads than backs, with the reduced locomotive patterns in forwards being due, potentially, to their primary role of contesting possession.

In another study involving southern hemisphere rugby union it was reported that rugby union players performed most of their sprints over distances between 10 m and 20 m, with forwards sprinting less often, on average, than backs, highlighting the importance of speed training for some positional groups (Duthie et al., 2006). Studies using time-motion analysis found that sprinting occurred on average 16 ± 15 and 23 ± 19 times for forwards and backs respectively, lasting on average 1.2 ± 0.2 s (Roberts et al., 2008). It is, however, important to note that many of the studies considered above, assessing game demands in rugby union, incorporated only the players that play the full game and therefore do not represent the full spectrum of playing positions and their requirements. As is commonly seen within elite modern rugby, many positional groups rarely complete the full duration of the game and instead are substituted in a pre-determined format, meaning that these players can be conditioned specifically for these particular match demands. Recent evidence illustrating this notion was presented by Lacome et al. (2015), who noted that 85.2% of substitutions were made for tactical reasons, with the mean period for non-injury substitutions varying between positional groups (Forwards 50-65 mins; Backs 70-75 mins). Also of interest from the research by Lacome et al. (2015), assessing international players using time-motion analysis, was the positive impact of substitutions upon match play (as represented by improved running performance; ES 0.2-0.5), therefore supporting the use of substitutions in order to improve match outcome.

Austin et al. (2011a) noted that forward walking and forward jogging comprised 65% of the total distance covered by front row forwards, compared to 63% for back row forwards, 56% for inside backs and 58% for outside backs. This amount of time either walking or jogging illustrates the nature of rugby union as an intermittent sport, with short periods of high intensity activity. Striding and sprinting accounted for 31%, 32%, 38% and 33% respectively for the above positions; with inside backs covering the greatest distance at sprinting speeds and front row forwards the smallest. High intensity runs are performed 41 ± 16 and 59 ± 28 times forwards and backs respectively lasting on average 1.3-1.5 s (Roberts et al, 2008). A measure of intensity is heart rate, where it was reported that high demands are placed on a player's cardiovascular system when players are required to reach 86% of their maximal heart rate (Cunniffe et al., 2009). Another performance aspect that adds to the match demands to which players are exposed, is that of "static holds". The scrum, maul and ruck elements of rugby union

were categorised by Austin et al. (2011a) as “static holds” and they reported that front row (11 ± 8 s) and back row (15 ± 9 s) forwards spent significantly more time in static hold positions compared to the inside and outside backs. Forwards perform high-intensity static exertion for longer periods, spending eight minutes in intense scrummaging, each lasting 5-20 s and 5 minutes in rucks and mauls contributing to 15% of total game time, compared to 4 minutes of high-intensity static exertion by the backs.

Distances covered and intensity of effort have been reported to have increased in rugby union since the advent of professionalism in 1995, with distances covered in excess of 5 m.s appearing more frequently in the international game, compared to other forms of the professional game (Quarrie et al., 2013). Data from Austin et al. (2013) showed changes of 2% increased sprinting time and a 7% decrease in time standing during match play, when comparing data with that of Duthie et al. (2006), collected from Super 12 rugby six years earlier. Cunniffe et al. (2009) revealed that the average number of total impacts in a game was > 1000 per game and McLellan and Lovell (2012) noted correlations between the total number of impacts experienced within elite rugby league match play and compromised neuromuscular function in the 48 hours post-match. Takarada (2003) concluded that although the direct impact of tackles on the body was considered to be the major cause of muscle damage, repeated intermittent sprinting was also a major contributor. Research in rugby union has noted that creatine kinase (CK) values (an indicator of muscle damage) relate specifically to physical impacts from games, with CK values post-match perhaps providing a basis for recovery strategies (Smart et al., 2008). It is likely that impacts during game time, identified from GPS units, do not solely arise from collisions but instead from a combination of movement and collisions, meaning that lower level impacts can be a result of activities such as deceleration, change of direction and landing in a lineout. McLellan and Lovell (2012) noted “very heavy” (8.1-10 G) and “severe” (>10.1 G) impacts to be significantly correlated with neuromuscular responses (peak rate of force development and peak power) 24 hours post-match. It is, however, important for practitioners to note that a 4 G classification from a collision occurring during a tackle, for example, might have a very different neuromuscular response to that of a 4 G classification from a change of direction.

A critical appraisal of GPS monitoring in team sports was conducted by Cummins et al. (2013), with six studies detailed across varying playing levels in rugby union, confirming the physical demands that are placed upon players and the specific metrics involved. GPS data is collected throughout rugby players training weeks and longitudinally over an entire playing season, with many studies published recently on game data (Austin et al., 2011a; Cahill et al., 2013; Coughlan et al., 2011; Quarrie et al., 2013). The need to analyse GPS data and the associated training volume (distances, speeds and impacts for example) has been utilised in many studies of rugby union (Austin et al., 2011a; Cahill et al., 2013; Coughlan et al., 2011) and is considered an essential tool of many elite sport teams. The detailed information collected, on both external load (i.e. distance) and internal load (i.e. heart rate), provides a more global assessment of exercise intensity. It is, however, of note to practitioners that the sampling frequency used within research varies, potentially resulting in differing values for many match demand metrics.

The aim of this study is to develop a greater understanding of match demands within elite rugby union and to identify differences between positions and positional groups. The novel aspect of this research is that the data used to measure match characteristics includes match data collected for players who played longer than 30 minutes, unlike earlier research, which only

focused upon match characteristics from players that played the entire match. It could be argued that solely assessing data involving players who played the entire match limits “real world” application. Implementation of the findings from the assessment of match data, which only encompasses the entire match, would perhaps underprepare players for the peak intensities experienced during match play, as the relative metrics (such as intensity) are likely to be higher amongst players who perform substitute roles. In line with earlier research (Austin et al., 2011a; Cahill et al., 2013; Cunningham et al., 2016), it was hypothesised that distance covered within games would be greater for backs than forwards and that backs would complete their activities at a greater intensity. It was also hypothesised, that forwards would experience a greater number of impacts > Zone 3 in match situations compared to backs and that backs would conduct a greater volume of accelerations and decelerations compared to forwards. Additionally, as was seen in previous research (Austin et al., 2011a; Cahill et al., 2013), it was hypothesised that of the nine positional groups; full backs, wingers and scrum halves, would cover the greatest distances and work at the highest intensities. Lastly, in a similar vein to previous findings (Coughlan et al., 2011; Venter et al., 2011), it was hypothesised that of the nine positional groups, back row forwards would experience the highest number of impacts > Zone 3 and that props, hookers and locks would experience the highest magnitude of impacts (measured in G-forces). The results from this study, showing varying match characteristics across a variety of match minutes, will help guide practitioners upon the required match demands of all nine positional groups. The additional knowledge gained as a result of this study, surrounding the influence of tactical substitutions and likely match demands upon positional demands, will also help guide future practice in modern rugby union.

3.3 Method

3.3.1 Experimental Approach

The assessment period covered thirty-two games and was collected throughout a competitive rugby union playing season. Data was collected from thirty-eight professional players, including data from some players who did not compete in every game; meaning that 462 sets of game data were assessed (age 26.4 ± 4.7 years, height 182.3 ± 30.2 cm, mass 100.0 ± 11.0 kg, training age 7.8 ± 4.6 years). A detailed breakdown of positions is included in Table 3.1 below. The GPS units used by the players were worn in bespoke pockets incorporated within their playing jerseys. They were positioned on the thoracic spine between the scapulae in order to reduce unnecessary movement during match play that might influence data collected.

Table 3.1: Physical characteristics of players assessed

Position	n	Age	Height (cm)	Bodyweight (kg)	Training Age (years)
All positions	462	26.3 ± 4.8	187.4 ± 6.4	100.1 ± 11.1	7.7 ± 4.6
Forwards	242	27.5 ± 5.0	189.4 ± 6.5	109.0 ± 8.0	8.9 ± 5.1
Backs	220	25.2 ± 4.4	185.4 ± 5.9	91.3 ± 5.3	6.5 ± 4.4
Prop	62	27.2 ± 5.5	184.7 ± 1.2	115.2 ± 9.8	7.0 ± 4.6
Hookers	30	23.6 ± 3.5	184.3 ± 4.0	106.3 ± 1.5	5.3 ± 4.0
Locks	59	31.0 ± 4.8	197.2 ± 2.8	116.5 ± 5.0	13.0 ± 4.8
Back Row	95	27.3 ± 5.0	189.8 ± 6.4	103.1 ± 3.8	9.2 ± 5.1
Scrum Half	34	26.3 ± 5.5	179.6 ± 2.8	85.3 ± 3.2	8.3 ± 5.5
Out Half	33	25.5 ± 2.1	184.0 ± 1.4	88.5 ± 4.9	7.5 ± 2.1
Centre	59	24.3 ± 5.4	185.8 ± 7.1	95.3 ± 5.88	4.6 ± 3.9
Wing	62	26.1 ± 4.2	187.1 ± 6.1	91.3 ± 3.6	7.6 ± 3.2
Full Back	27	23.5 ± 4.9	189.5 ± 2.1	91.5 ± 3.5	5.5 ± 4.9

Participants were advised to maintain their usual recovery process post-match during the testing period, including nutritional interventions or active swim recovery sessions. On average, each week consisted of two resistance training sessions and five rugby sessions, with the training volume tapering on a weekly basis as game day approached (Table 3.2). This study was conducted in accordance with the Declaration of Helsinki and was approved by Salford University Institutional Review Board. All participants provided written informed consent to participate in this study.

Table 3.2: Example training week

Microcycle and time of day	GAME DAY	+1	+2	+3	+4	+5	+6
AM		Club Prescribed Recovery with Team	Rest Day	Weights & Units Rugby	Rugby Team Session	Rest Day	Rugby Team Session
PM	Game			Rugby Team Session	Weights		

3.3.2 Match analysis

All matches within this study were played during the competitive playing season of an English Premiership Rugby Union team over a period of nine months, with data only included when players played ≥ 30 minutes. The rationale for the inclusion of data when players played ≥ 30 minutes, was that this is typically the smallest number of minutes played considered large enough for measurement. Players who played less than 30 minutes were considered as not having completed typical match demands and would therefore represent an inaccurate measure of match characteristics. When combining this view with the commonly seen practice within professional rugby union of substituting players at around the 50 minute time-point, for tactical reasons rather than injury, further rationale for selecting players who played ≥ 30 minutes for analysis is evident.

Measurements were conducted on players from one club with 10 Hz GPS units (*StatSports Viper*, Northern Ireland) being used throughout all games to assess movement patterns. Reliability of GPS analysis in team sport settings has been confirmed in many previous studies (Coutts & Duffield, 2010; Cummins et al., 2013; Johnston, Watsford, Kelly, Pine, & Spurrs, 2014; Varley, Fairweather, & Aughey, 2012), with Coutts and Duffield (2010) reporting total distance being stable between match variations in rugby league ($<5\%$ CV), while Johnston, Watsford, et al. (2014) showed a larger degree of between match variability for higher speed activities (TEM = 0.8-19.9%) also in rugby league.

Player positions were defined as: backs or forwards; further subdivided into; props, hookers, locks, back rows, scrum half, out half, centres, wings and full backs. The match characteristics assessed included [game time, distance covered, intensity, accelerations, decelerations, impacts $> \text{Zone 3}$, Distance in Zone 1 (D1), Distance in Zone 2 (D2), Distance in Zone 3 (D3), Distance in Zone 4 (D4), Distance in Zone 5 (D5), Distance in Zone 6 (D6), Impacts in Zone 1 (Im1), Impacts in Zone 2 (Im2), Impacts in Zone 3 (Im3), Impacts in Zone 4 (Im4), Impacts in Zone 5 (Im5) and

Impacts in Zone 6 (Im6)]. The specific categorisation of the speed and impact zones are detailed in Table 3.3 below.

The dependent variables assessed from the GPS data were; total distance covered, game time played, intensity, accelerations, decelerations and GPS impacts. Intensity was measured as average movement velocity across the game (m/min). The GPS device (which includes a 100 Hz 3-D accelerometer) measures GPS impacts when values are above 2 G in a 0.1 second period. Impacts are instantaneous moments throughout a training or match situation, measured in G-forces and expressed as a quantity, with a number of impacts at each of the 6 zones categorised in the *Viper* system. It is important to note, that GPS impacts are a combination of collision and impacts created from movement (stepping, jumping, and decelerations). The number of accelerations and decelerations was measured via the accelerometer, with individually prescribed zones categorised for each individual regards speed aiding to signify accelerations, decelerations and distance covered in speed zones.

Table 3.3: Categorisation of distances covered and impacts

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Speed (m/s)	0 – 1.5	1.51 – 3.0	3.01 – 4.0	4.01 – 5.5	5.51 – 7.0	7.01 +
Speed (km/h)	0 – 5.40	5.41 – 10.80	10.81 – 14.40	14.41 – 19.80	19.81 – 25.20	25.21 +
Impacts in Zones (G)	3 - 5	5 – 7	7 - 9	9 - 11	11 - 13	>13

3.3.3 Statistical Analyses

Statistical analysis was performed using SPSS Version 20 (IBM), with an *a priori* alpha level set at $p < 0.05$. Normality of analysed variables was assessed using Shapiro-Wilks test between positional groups (forwards and backs) and across positions (props, hookers, locks, back rows, scrum half, out half, centres, wings and full backs). Absolute values for all positions were assessed in order to determine the influence of positions on each of the match characteristics, regardless of the number of minutes they played. Differences between forwards and backs were determined using Wilcoxon signed ranks tests.

Non-parametric Friedman tests were conducted in order to determine differences between each position for each variable, with multiple pairwise comparisons performed using Wilcoxon tests, including subsequent Bonferroni correction, in order to assess where the difference occurred. Cohen's *d* effect sizes (ES) were used to assess the magnitude of any effect in accordance with Rhea (2004) and interpreted as follows; trivial = < 0.25 , small = $0.25 - 0.5$, moderate = $0.50 - 1.0$ and large > 1.0 . Post-hoc statistical power was calculated using G Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009).

3.4 Results

3.4.1 Match characteristics between forwards and backs

Shapiro Wilks tests of normality revealed that all match characteristics for forwards, (excluding intensity, Im1 and Im2), were not normally distributed ($p > 0.05$). For backs, Shapiro Wilks tests of normality revealed that all match characteristics, (excluding intensity, accelerations, decelerations and D5), were not normally distributed ($p > 0.05$).

The Wilcoxon tests showed that backs played at a significantly ($p < 0.001$) greater intensity, with a large effect size reported. Backs also demonstrated a greater number of impacts in Zone

1 compared to the forwards, although the difference between positions was small (Table 3.4 and Table 3.5). Additionally, Wilcoxon tests showed that forwards performed a significantly ($p < 0.001$) greater number of accelerations and decelerations, with a moderate difference noted. Backs covered more distance in D5 compared to forwards, with a large difference between positional groups. Wilcoxon tests identified that backs performed significantly ($p < 0.001$) more game time, distance covered in D1, D4, D6, compared to forwards (Table 3.4), with a moderate to large difference between positional groups noted.

Table 3.4: Descriptive statistics (mean \pm standard deviations; CI=95% confidence intervals), effects sizes and statistical power, across distance data for forwards and backs

Position	Forwards	Backs	Cohen's <i>d</i>	Effect	Statistical Power
Game Time (mins)	66.6 \pm 14.8 (CI 64.8-68.5)	71.6 \pm 13.0* (CI 69.9-73.3)	0.35	Small	1.00
Distance (m)	5035 \pm 1157 (CI 4890-5179)	5918 \pm 1206* (CI 5758-6078)	0.74	Moderate	1.00
Intensity (m/min)	64.0 \pm 6.3 (CI 63.2-64.8)	70.9 \pm 7.4* (CI 69.9-71.8)	1.00	Moderate	1.00
Accelerations	22.0 \pm 11.9 (CI 20.5-23.5)	32.2 \pm 10.6* (CI 30.8-33.6)	0.90	Moderate	1.00
Decelerations	30.8 \pm 14.4 (CI 29.0-32.6)	41.9 \pm 12.3* (CI 40.3-43.6)	0.82	Moderate	1.00
Distance Zone 1 (m)	1898 \pm 450 (CI 1443-1555)	2195 \pm 542* (CI 2123-2267)	0.59	Moderate	1.00
Distance Zone 2 (m)	1499 \pm 494 (CI 1836-1960)	1558 \pm 399 (CI 1505-1610)	0.13	Trivial	0.88
Distance Zone 3 (m)	914 \pm 264 (CI 881-947)	904 \pm 243 (CI 871-936)	0.04	Trivial	0.23
Distance Zone 4 (m)	531 \pm 232 (CI 502-560)	804 \pm 245* (CI 771-836)	1.14	Large	1.00
Distance Zone 5 (m)	153 \pm 97 (CI 141-165)	322 \pm 119* (CI 306-338)	1.07	Large	1.00
Distance Zone 6 (m)	14 \pm 19 (CI 12-17)	77 \pm 66* (CI 68-86)	1.29	Large	1.00
* $p < 0.001$					

Table 3.5: Descriptive statistics (mean \pm standard deviations; CI=95% confidence intervals), effect sizes and statistical power, across impact zones for forwards and backs

Position	Forwards	Backs	Cohen's <i>d</i>	Effect	Statistical Power
Impacts > Zone 3	229 \pm 160 (CI 209-249)	226 \pm 151 (CI 206-246)	0.01	Trivial	0.10
Impacts Zone 1	1836 \pm 604 (CI 1760-1911)	2054 \pm 546* (CI 1981-2126)	0.37	Small	1.00
Impacts Zone 2	811 \pm 243 (CI 781-841)	857 \pm 297 (CI 817-896)	0.16	Trivial	0.97
Impacts Zone 3	301 \pm 133 (CI 285-318)	312 \pm 154 (CI 292-333)	0.07	Trivial	0.50
Impacts Zone 4	114 \pm 79 (CI 104-124)	118 \pm 79 (CI 107-128)	0.05	Trivial	0.28
Impacts Zone 5	48 \pm 41 (CI 43-53)	47 \pm 38 (CI 42-53)	0.02	Trivial	0.13
Impacts Zone 6	66 \pm 44 (CI 60-71)	59 \pm 40# (CI 53-64)	0.16	Trivial	0.97
* $p = 0.001$ # $p = 0.03$					

3.4.2 Match characteristics between the nine positional groups

Shapiro Wilks tests of normality revealed that all match characteristics were not normally distributed ($p < 0.05$) across the nine positional groups. Friedman tests showed significant differences between positional groups for all the match characteristics variables, excluding D3, where no significant differences were observed ($p > 0.05$).

Pairwise comparisons demonstrated that game time was the greatest among the full backs and that this was significantly greater compared to props ($p = 0.003$, $d = 1.37$), hookers ($p = 0.010$, $d = 1.55$) and scrum halves ($p = 0.015$, $d = 1.32$), although not significantly different ($p > 0.05$) compared to the other positional groups. By contrast, hookers demonstrated the lowest values for game time, which was significantly lower than locks ($p = 0.036$, $d = 0.99$), back row ($p = 0.011$, $d = 0.92$), centres ($p > 0.001$, $d = 1.43$), wing ($p = 0.001$, $d = 1.08$) and full back ($p = 0.010$, $d = 1.55$), although not significantly different ($p > 0.05$) compared to the other positional groups (Table 3.6).

Full backs demonstrated the greatest intensity during match play, which was significantly greater compared to props ($p = 0.001$, $d = 2.88$), hookers ($p < 0.001$, $d = 1.71$), locks ($p < 0.001$, $d = 1.53$), back row ($p < 0.001$, $d = 1.94$), out halves ($p = 0.036$, $d = 0.76$) and wingers ($p = 0.036$, $d = 1.15$) although not significantly different ($p > 0.05$) compared to the other positional groups. In contrast, props competed at the lowest intensity, which was significantly lower than hookers ($p = 0.001$, $d = 1.377$), locks ($p < 0.001$, $d = 1.133$), back row ($p < 0.001$, $d = 0.945$), scrum halves ($p < 0.001$, $d = 2.476$), out halves ($p < 0.001$, $d = 2.341$), centres ($p < 0.001$, $d = 1.234$), wingers ($p < 0.001$, $d = 1.587$) and full backs ($p = 0.001$, $d = 2.881$) (Table 3.6).

Out halves performed the most accelerations, which was significantly greater than props ($p < 0.001$, $d = 2.71$), hookers ($p < 0.001$, $d = 1.58$), locks ($p = 0.006$, $d = 1.11$), although not significantly different ($p > 0.05$) compared to back row, scrum halves, centres, wingers and full backs. In contrast, props demonstrated the lowest values for accelerations, which was significantly lower than locks ($p < 0.001$, $d = 1.57$), back row ($p < 0.001$, $d = 1.02$), scrum halves ($p < 0.001$, $d = 1.97$), out halves ($p < 0.001$, $d = 2.71$), centres ($p < 0.001$, $d = 1.94$), wingers ($p < 0.001$, $d = 2.18$) and full backs ($p < 0.001$, $d = 2.61$), although not significantly different ($p > 0.05$) compared to hookers (Table 3.6).

Full backs performed the most decelerations, which was significantly greater than props ($p < 0.001$, $d = 2.91$) and hookers ($p < 0.001$, $d = 1.57$), although not significantly different ($p > 0.05$) compared to the other positional groups. In contrast, props demonstrated the lowest values for accelerations, which was significantly lower compared to locks ($p < 0.001$, $d = 1.51$), back row ($p < 0.001$, $d = 1.20$), scrum halves ($p < 0.001$, $d = 1.72$), out halves ($p < 0.001$, $d = 2.17$), centres ($p < 0.001$, $d = 2.48$), wingers ($p < 0.001$, $d = 2.05$) and full backs ($p < 0.001$, $d = 2.91$), although not significantly different ($p > 0.05$) compared to hookers (Table 3.6).

Table 3.6: Descriptive statistics (mean \pm standard deviations; CI=95% confidence intervals) across selected match demands data for all positions

Position	Prop	Hooker	Lock	Back Row	Scrum Half	Out Half	Centre	Wing	Full Back
Game Time (mins)	61.2 ± 14.2 (CI 57.7-64.8)	56.6 ± 16.8 (CI 50.6-60.5)	70.6 ± 10.8 (CI 67.7-73.4)	70.9 ± 14.3 (CI 68.0-73.8)	63.7 ± 11.8 (CI 59.5-67.8)	66.3 ± 14.2 (CI 64.1-71.3)	76.0 ± 9.4 (CI 73.5-78.4)	73.2 ± 13.9 (CI 69.7-76.7)	77.0 ± 8.0 (CI 73.8-80.1)
Intensity (m/min)	59.6 ± 5.4 (CI 58.2-60.9)	66.7 ± 4.9 (CI 64.9-68.4)	66.5 ± 6.7 (CI 64.7-68.2)	64.8 ± 5.6 (CI 63.6-65.9)	74.4 ± 6.5 (CI 72.1-76.6)	71.9 ± 5.1 (CI 70.1-73.7)	68.1 ± 8.1 (CI 65.9-70.2)	69.0 ± 6.4 (CI 67.4-70.7)	76.2 ± 6.1 (CI 73.8-78.6)
Accelerations	13.6 ± 7.0 (CI 11.9-15.3)	21.5 ± 9.9 (CI 18.0-25.0)	26.6 ± 9.3 (CI 24.1-29.0)	24.7 ± 13.6 (CI 21.9-27.4)	31.5 ± 10.7 (CI 27.7-35.2)	37.5 ± 10.3 (CI 33.9-41.1)	29.2 ± 8.9 (CI 26.9-31.5)	34.1 ± 11.3 (CI 31.2-37.0)	32.6 ± 7.5 (CI 29.6-35.5)
Decelerations	20.3 ± 7.7 (CI 18.4-22.2)	28.9 ± 11.8 (CI 24.7-33.1)	34.5 ± 10.8 (CI 31.6-37.3)	36.0 ± 16.7 (CI 32.6-39.4)	35.1 ± 9.4 (CI 31.8-38.4)	43.4 ± 12.9 (CI 38.8-47.9)	43.6 ± 10.8 (CI 40.8-46.5)	42.8 ± 13.4 (CI 39.4-46.2)	46.0 ± 9.8 (CI 42.1-48.9)
Key for p values falling within the following ranges:									
Ψ significantly greater (p<0.001) compared to Props					Ⓢ significantly greater (p<0.001) compared to Back Row				
μ significantly greater (0.001≤p<0.01) compared to Props					ξ significantly greater (0.001≤p<0.01) compared to Back Row				
û significantly greater (0.01≤p<0.05) compared to Props					Λ significantly greater (0.01≤p<0.05) compared to Back Row				
α significantly greater (p<0.001) compared to Hookers					★ significantly greater (0.01≤p<0.05) compared to Scrum Halves				
‡ significantly greater (0.001≤p<0.01) compared to Hookers					Ω significantly greater (0.01≤p<0.05) compared to Out Halves				
+ significantly greater (0.01≤p<0.05) compared to Hookers									
¥ significantly greater (p<0.001) compared to Locks					Ⓐ significantly greater (0.01≤p<0.05) compared to Wings				
v significantly greater (0.001≤p<0.01) compared to Locks									
ŵ significantly greater (0.01≤p<0.05) compared to Locks									

Full backs covered the greatest distance, which was significantly greater compared to props ($p < 0.001$, $d = 3.19$), hookers ($p < 0.001$, $d = 2.39$), locks ($p < 0.001$, $d = 1.60$), back row ($p < 0.001$, $d = 1.55$), scrum halves ($p = 0.001$, $d = 1.73$) and out halves ($p = 0.003$, $d = 1.33$), although not significantly different ($p > 0.05$) compared to the other positional groups. In contrast, props covered the lowest distance which was significantly lower than locks ($p < 0.001$, $d = 1.31$), back row ($p < 0.001$, $d = 1.10$), scrum halves ($p = 0.002$, $d = 1.20$), out halves ($p < 0.001$, $d = 1.23$), centres ($p < 0.001$, $d = 1.89$), wingers ($p < 0.001$, $d = 1.48$) and full backs ($p < 0.001$, $d = 3.19$), although not significantly different ($p > 0.05$) compared to hookers (Table 3.7).

Centres covered the greatest distance in Zone 1 (D1), which was significantly greater compared to props ($p < 0.001$, $d = 1.28$), hookers ($p < 0.001$, $d = 2.10$), locks ($p < 0.001$, $d = 0.94$), back row ($p = 0.001$, $d = 0.77$) scrum halves ($p < 0.001$, $d = 1.69$) and out halves ($p = 0.78$, $d = 3.193$), although not significantly different ($p > 0.05$) compared to the other positional groups. In contrast, hookers demonstrated the lowest values for D1, which was significantly lower than back row ($p = 0.002$, $d = 1.24$), centres ($p < 0.001$, $d = 2.10$), wingers ($p = 0.001$, $d = 1.72$) and full back ($p < 0.001$, $d = 2.12$), although not significantly different ($p > 0.05$) compared to the other positional groups (Table 3.7).

Full backs covered the greatest distance in Zone 2 (D2) which was significantly greater compared to props ($p < 0.001$, $d = 3.47$), hookers ($p = 0.003$, $d = 1.79$), locks ($p = 0.036$, $d = 0.98$), back row ($p = 0.005$, $d = 1.24$), scrum halves ($p < 0.001$, $d = 2.39$), out halves ($p < 0.001$, $d = 2.34$), centres ($p = 0.001$, $d = 1.63$) and wingers ($p = 0.003$, $d = 1.484$). In contrast, props demonstrated the lowest values for D2, which was significantly lower than hookers ($p = 0.036$, $d = 1.11$), locks ($p < 0.001$, $d = 2.00$), back row ($p < 0.001$, $d = 1.76$), scrum halves ($p = 0.002$, $d = 1.27$), out halves ($p = 0.002$, $d = 1.34$), centres ($p < 0.001$, $d = 1.61$), wingers ($p < 0.001$, $d = 0.83$) and full backs ($p < 0.001$, $d = 3.47$) (Table 3.7).

Locks covered the greatest distance in Zone 3 (D3), which was significantly greater, compared to props ($p = 0.002$, $d = 0.75$), and centre ($p = 0.004$, $d = 0.82$), although not significantly different ($p > 0.05$) compared to the other positional groups. In contrast, centres demonstrated the lowest values for D3, which was significantly lower than locks ($p = 0.004$, $d = 0.82$), although not significantly different ($p > 0.05$) compared to the other positional groups (Table 3.7).

Scrum halves covered the greatest distance in Zone 4 (D4) which was significantly greater compared props ($p < 0.001$, $d = 3.51$), hookers ($p < 0.001$, $d = 2.16$), locks ($p < 0.001$, $d = 1.84$), back row ($p < 0.001$, $d = 1.87$), out halves ($p = 0.036$, $d = 0.72$), centres ($p = 0.002$, $d = 1.28$) and wingers ($p = 0.010$, $d = 1.35$), although not significantly different ($p > 0.05$) compared to full backs. In contrast, props demonstrated the lowest values for D4, which was significantly lower than locks ($p < 0.001$, $d = 1.02$), back row ($p < 0.001$, $d = 0.87$), scrum halves ($p < 0.001$, $d = 3.51$), out halves ($p < 0.001$, $d = 2.48$), centres ($p < 0.001$, $d = 2.19$), wingers ($p < 0.001$, $d = 1.69$) and full backs ($p < 0.001$, $d = 3.45$), although not significantly different ($p > 0.05$) compared to hookers (Table 3.7).

Full backs covered the greatest distance in Zone 5 (D5) which was significantly greater than props ($p < 0.001$, $d = 3.36$), hookers ($p < 0.001$, $d = 3.96$), locks ($p < 0.001$, $d = 3.12$), back row ($p < 0.001$, $d = 1.91$), scrum halves ($p = 0.002$, $d = 1.49$) and out halves ($p = 0.001$, $d = 1.49$),

although not significantly different ($p > 0.05$) compared to centres and wingers. In contrast, hookers demonstrated the lowest values for D5, which was significantly lower compared to props ($p < 0.036$, $d = 0.87$), locks ($p < 0.001$, $d = 1.36$), back row ($p < 0.001$, $d = 1.42$), scrum halves ($p < 0.001$, $d = 3.29$), out halves ($p < 0.001$, $d = 2.83$), centres ($p < 0.001$, $d = 3.01$), wingers ($p < 0.001$, $d = 2.73$) and full backs ($p < 0.001$, $d = 2.59$) (Table 3.7).

Wingers covered the greatest distance in Zone 6 (D6) which was significantly greater than props ($p < 0.001$, $d = 2.28$), hookers ($p < 0.001$, $d = 2.62$), locks ($p < 0.001$, $d = 2.59$), back row ($p < 0.001$, $d = 2.21$) scrum halves ($p < 0.001$, $d = 1.99$), out halves ($p < 0.001$, $d = 1.69$) and centres ($p < 0.001$, $d = 1.49$), although not significantly different ($p > 0.05$) compared to and full backs. In contrast, hookers demonstrated the lowest values for D6, which was significantly lower than props ($p = 0.007$, $d = 0.73$), back row ($p = 0.010$, $d = 0.87$) scrum halves ($p < 0.001$, $d = 1.76$), out halves ($p < 0.001$, $d = 1.51$), centres ($p < 0.001$, $d = 1.53$), wingers ($p < 0.001$, $d = 2.62$) and full backs ($p < 0.001$, $d = 2.69$), although not significantly different ($p > 0.05$) compared to locks (Table 3.7).

Table 3.7: Descriptive statistics (mean \pm standard deviations; CI=95% confidence intervals) across distance data for all positions (symbols presented on Table 3.8)

Position	Prop	Hooker	Lock	Back Row	Scrum Half	Out Half	Centre	Wing	Full Back
Distance (m)	4285 \pm 893	4469 \pm 1238	5517 \pm 979 Ψ	5411 \pm 1134 Ψ X	5408 \pm 978 #	5583 \pm 1191 #	6043 \pm 966 Ψ Γ	5926 \pm 1295 Ψ €	6904 \pm 740 Ψ € ^ \$ £ €
	(CI 4065-4505)	(CI 4029-4908)	(CI 5259-5774)	(CI 5181-5641)	(CI 5067-5750)	(CI 5167-5999)	(CI 5791-6295)	(CI 5597-6255)	(CI 6617-7191)
Distance Zone 1 (m)	1799 \pm 487	1474 \pm 429	1963 \pm 479	2043 \pm 482 Γ	1692 \pm 381	2029 \pm 499	2405 \pm 456 Ψ € ^ @ ξ V	2337 \pm 562 Ψ Γ W E H	2328 \pm 371 € # W E
	(CI 1679-1919)	(CI 1322-1627)	(CI 1837-2089)	(CI 1945-2141)	(CI 1559-1825)	(CI 1855-2203)	(CI 2286-2524)	(CI 2194-2480)	(CI 2184-2472)
Distance Zone 2 (m)	1043 \pm 319	1451 \pm 410 H	1748 \pm 383 Ψ @	1663 \pm 382 Ψ H	1421 \pm 273 #	1439 \pm 269 #	1574 \pm 338 Ψ	1446 \pm 400 Ψ	2078 \pm 275 Ψ @ € Γ @ ξ u W
	(CI 965-1122)	(CI 1306-1597)	(CI 1647-1849)	(CI 1586-1741)	(CI 1325-1716)	(CI 1345-1533)	(CI 1485-1662)	(CI 1344-1548)	(CI 1971-2185)
Distance Zone 3 (m)	847 \pm 210	926 \pm 296	1046 \pm 306 # u	863 \pm 244	971 \pm 217	948 \pm 228	824 \pm 225	861 \pm 263	1042 \pm 199
	(CI 795-899)	(CI 821-1031)	(CI 965-1127)	(CI 814-913)	(CI 895-1047)	(CI 869-1028)	(CI 766-883)	(CI 794-928)	(CI 965-1119)
Distance Zone 4 (m)	394 \pm 124	536 \pm 223	589 \pm 240 Ψ	568 \pm 254 Ψ	1009 \pm 214 Ψ € ^ \$ u @ V	848 \pm 227 ^ Ψ Γ	748 \pm 191 Ψ ξ H H	708 \pm 230 Ψ	922 \pm 177 Ψ € ^
	(CI 364-425)	(CI 457-615)	(CI 526-580)	(CI 517-620)	(CI 934-1084)	(CI 769-927)	(CI 698-798)	(CI 650-767)	(CI 853-991)
Distance Zone 5 (m)	118 \pm 56 X	73 \pm 47	142 \pm 54 €	202 \pm 119 € #	281 \pm 76 Ψ € ^ H	273 \pm 88 Ψ € ^	322 \pm 107 Ψ € ^ \$	346 \pm 113 Ψ € ^ \$	429 \pm 118 Ψ € ^ \$ £ €
	(CI 104-131)	(CI 57-90)	(CI 127-156)	(CI 178-226)	(CI 254-308)	(CI 242-304)	(CI 294-350)	(CI 317-374)	(CI 384-475)
Distance Zone 6 (m)	17 \pm 23 Γ	4 \pm 10	6 \pm 9	20 \pm 24 W X	33 \pm 21 ^ €	43 \pm 35 ^ € H	51 \pm 42 \$ Ψ € ^	139 \pm 72 Ψ € ^ \$ @ € A	101 \pm 50 Ψ € ^ \$ £ V
	(CI 11-23)	(CI 1-8)	(CI 3-8)	(CI 15-25)	(CI 25-40)	(CI 31-55)	(CI 40-62)	(CI 120-157)	(CI 82-121)

Table 3.8: Key for descriptive distance data in Table 3.7

<p>Key for p values falling within the following ranges:</p> <p>Ψ significantly greater ($p < 0.001$) compared to Props</p> <p># significantly greater ($0.001 \leq p < 0.01$) compared to Props</p> <p>û significantly greater ($0.01 \leq p < 0.05$) compared to Props</p> <p>€ significantly greater ($p < 0.001$) compared to Hookers</p> <p>Γ significantly greater ($0.001 \leq p < 0.01$) compared to Hookers</p> <p>χ significantly greater ($0.01 \leq p < 0.05$) compared to Hookers</p> <p>^ significantly greater ($p < 0.001$) compared to Locks</p> <p>ŵ significantly greater ($0.001 \leq p < 0.01$) compared to Locks</p> <p>ϣ significantly greater ($0.01 \leq p < 0.05$) compared to Locks</p> <p>\$ significantly greater ($p < 0.001$) compared to Back Row</p> <p>ξ significantly greater ($0.001 \leq p < 0.01$) compared to Back Row</p> <p>ϣ significantly greater ($0.01 \leq p < 0.05$) compared to Back Row</p>	<p>Ⓔ significantly greater ($p < 0.001$) compared to Scrum Halves</p> <p>£ significantly greater ($0.001 \leq p < 0.01$) compared to Scrum Halves</p> <p>★ significantly greater ($0.01 \leq p < 0.05$) compared to Scrum Halves</p> <p>▣ significantly greater ($p < 0.001$) compared to Out Halves</p> <p>€ significantly greater ($0.001 \leq p < 0.01$) compared to Out Halves</p> <p>∨ significantly greater ($0.01 \leq p < 0.05$) compared to Out Halves</p> <p>A significantly greater ($p < 0.001$) compared to Out Halves</p> <p>u significantly greater ($0.001 \leq p < 0.01$) compared to Centre</p> <p>♣ significantly greater ($0.001 \leq p < 0.01$) compared to Wingers</p> <p>® significantly greater ($0.01 \leq p < 0.05$) compared to Wingers</p>
---	--

Impacts > Zone 3 showed the highest values among the full backs which was significantly greater compared to locks ($p = 0.001$, $d = 1.84$), back row ($p = 0.003$, $d = 0.68$), out half ($p = 0.036$, $d = 1.24$) and wingers ($p = 0.036$, $d = 0.76$), although not significantly different ($p > 0.05$) compared to props, hookers, scrum half and centres. In contrast, locks demonstrated the lowest values for Impacts > Zone 3, which was significantly different to hookers ($p < 0.001$, $d = 1.25$), scrum halves ($p = 0.002$, $d = 1.10$) and full backs ($p = 0.001$, $d = 1.84$), although not significantly different ($p > 0.05$) compared to props, back row, out halves, centres and wingers (Table 3.9).

Im1 showed the highest values among the full backs which was significantly greater than props ($p < 0.001$, $d = 3.24$), hookers ($p = 0.009$, $d = 1.38$), scrum halves ($p = 0.036$, $d = 1.03$), out halves ($p = 0.036$, $d = 0.98$) and wingers ($p = 0.012$, $d = 1.26$), although not significantly different ($p > 0.05$) compared to lock, back row and centres. In contrast, props demonstrated the lowest values for Im1, which was significantly lower compared to hookers ($p = 0.001$, $d = 1.43$), locks ($p < 0.001$, $d = 2.41$), back row ($p < 0.001$, $d = 2.08$), scrum halves ($p < 0.001$, $d = 1.79$), out halves ($p < 0.001$, $d = 1.99$), centres ($p < 0.001$, $d = 2.28$), wingers ($p < 0.001$, $d = 1.68$) and full backs ($p < 0.001$, $d = 3.24$) (Table 3.9).

Im2 showed the highest values among the scrum halves which was significantly greater compared to props ($p < 0.001$, $d = 1.81$), locks ($p < 0.001$, $d = 0.72$), back row ($p = 0.009$, $d = 1.20$), centres ($p = 0.030$, $d = 1.18$), wingers ($p = 0.002$, $d = 1.47$) and full backs ($p = 0.030$, $d = 0.097$), although not significantly different ($p > 0.05$) compared to hookers and out halves. In contrast, props demonstrated the lowest values for Im2, which was significantly different to locks ($p = 0.013$, $d = 0.65$), scrum half ($p < 0.001$, $d = 1.81$), out half ($p = 0.015$, $d = 1.02$) and full back ($p = 0.036$, $d = 0.98$), although not significantly different ($p > 0.05$) compared to the other positional groups hookers, back row, centres and wingers (Table 3.9).

Im3 showed the highest values among the scrum halves which was significantly greater than locks ($p < 0.001$, $d = 1.68$), back row ($p = 0.004$, $d = 1.02$), out halves ($p = 0.009$, $d = 1.03$) and wingers ($p = 0.008$, $d = 1.17$), although not significantly different ($p > 0.05$) compared to props, hookers, centres and full backs. In contrast, locks demonstrated the lowest values for Im3, which was significantly lower than props ($p < 0.001$, $d = 0.87$), hookers ($p = 0.001$, $d = 1.19$), scrum half ($p < 0.001$, $d = 1.68$), out half ($p = 0.005$, $d = 0.84$) and full back ($p = 0.003$, $d = 1.30$), although not significantly different ($p > 0.05$) compared to back row, centres and wingers (Table 3.9).

Im4 showed the highest values among the scrum halves which was significantly greater compared to back row ($p = 0.036$, $d = 0.69$), out half ($p = 0.036$, $d = 0.86$) and centres ($p < 0.001$, $d = 0.55$), although not significantly different ($p > 0.05$) compared to props, hookers, locks, wingers and full backs. In contrast, locks demonstrated the lowest values for Im4, which was significantly lower compared to hookers ($p < 0.001$, $d = 1.24$), scrum half ($p < 0.001$, $d = 1.43$), out half ($p = 0.004$, $d = 0.91$) and full back ($p = 0.001$, $d = 1.66$), although not significantly different ($p > 0.05$) compared to props, back row, centres and wingers (Table 3.9).

Im5 showed the highest values among the full backs which was significantly greater compared to locks ($p = 0.001$, $d = 1.78$), back row ($p = 0.003$, $d = 0.75$), out halves ($p = 0.036$, $d = 1.22$) and wingers ($p = 0.036$, $d = 0.77$), although not significantly different ($p > 0.05$)

compared to props, hookers, scrum halves and centres. In contrast, locks demonstrated the lowest values for Im5, which was significantly lower compared to hookers ($p < 0.001$, $d = 1.25$) and full back ($p = 0.001$, $d = 1.78$), although not significantly different ($p > 0.05$) compared to props, back row, out halves, centres and wingers (Table 3.9).

Im6 showed the highest values among the full backs which was significantly greater compared to locks ($p = 0.006$, $d = 1.73$), back row ($p = 0.030$, $d = 0.74$), scrum halves ($p = 0.005$, $d = 1.29$), out halves ($p = 0.001$, $d = 1.92$) and wingers ($p = 0.011$, $d = 0.85$), although not significantly different ($p > 0.05$) compared to props, hookers and centres. In contrast, out half demonstrated the lowest values for Im6, which was significantly lower compared to hookers ($p = 0.003$, $d = 1.41$), back row ($p = 0.007$, $d = 1.07$), centres ($p = 0.003$, $d = 0.72$) and full back ($p = 0.001$, $d = 1.92$), although not significantly different ($p > 0.05$) compared to props, locks, scrum halves and wingers (Table 3.9).

Table 3.9: Descriptive statistics (mean \pm standard deviations; CI=95% confidence intervals) across impacts data for all positions

Position	Prop	Hooker	Lock	Back Row	Scrum Half	Out Half	Centre	Wing	Full Back
Impacts > Zone 3	259 ± 250 (CI 198-321)	291 ± 145 § Ψ (CI 239-342)	157 ± 40 (CI 146-167)	225 ± 109 (CI 203-247)	274 ± 145 θ (CI 223-324)	186 ± 77 (CI 159-213)	229 ± 186 (CI 180-278)	197 ± 155 (CI 158-237)	296 ± 99 θ Ψ Π Ω (CI 257-334)
Impacts Zone 1	1178 ± 313 (CI 1100-1255)	1820 ± 549 ^ (CI 1625-2015)	2232 ± 533 § (CI 2092-2373)	2019 ± 476 § (CI 1922-2115)	1998 ± 566 § (CI 1800-2195)	2042 ± 528 § (CI 1857-2226)	2053 ± 441 § (CI 1938-2168)	1901 ± 521 § (CI 1768-2033)	2553 ± 510 § ▫ v Ω Ψ (CI 2355-2751)
Impacts Zone 2	716 ± 195 (CI 668-764)	900 ± 326 (CI 785-1016)	845 ± 201 α (CI 792-898)	815 ± 259 (CI 762-868)	1107 ± 234 § § ρ σ Δ Π (CI 1025-1188)	948 ± 255 ^ (CI 859-1038)	762 ± 337 (CI 674-850)	748 ± 252 (CI 684-812)	902 ± 182 α (CI 832-973)
Impacts Zone 3	323 ± 128 § (CI 292-355)	379 ± 158 θ (CI 323-435)	231 ± 76 (CI 211-251)	294 ± 135 (CI 267-322)	449 ± 166 § ρ χ σ (CI 391-507)	307 ± 102 θ (CI 271-343)	274 ± 177 (CI 228-320)	273 ± 132 (CI 239-307)	341 ± 92 θ (CI 306-377)
Impacts Zone 4	130 ± 114 (CI 102-158)	148 ± 79 § Ψ (CI 120-176)	75 ± 25 (CI 69-82)	112 ± 59 (CI 99-124)	162 ± 82 § Π Ω (CI 133-191)	106 ± 41 θ (CI 91-120)	111 ± 101 (CI 85-138)	100 ± 73 (CI 82-119)	142 ± 51 θ (CI 122-162)
Impacts Zone 5	57 ± 67 (CI 40-73)	62 ± 35 § χ σ Π (CI 49-75)	30 ± 9 (CI 28-33)	46 ± 26 (CI 41-51)	58 ± 37 § (CI 45-72)	37 ± 20 (CI 29-44)	48 ± 48 (CI 35-61)	41 ± 37 (CI 31-50)	66 ± 27 θ ρ Ω Ψ (CI 55-76)
Impacts Zone 6	70 ± 74 (CI 51-88)	80 ± 33 θ χ σ v (CI 68-92)	49 ± 15 (CI 45-53)	67 ± 27 χ ω (CI 61-72)	52 ± 27 (CI 43-62)	42 ± 19 (CI 36-49)	66 ± 43 Ω (CI 54-77)	53 ± 49 (CI 40-65)	87 ± 27 θ τ χ Π Ψ (CI 76-97)

Key for p values falling within the following ranges:

§ significantly greater (p<0.001) compared to Props

^ significantly greater (0.001≤p<0.01) compared to Props

α significantly greater (0.01≤p<0.05) compared to Props

▫ significantly greater (0.001≤p<0.01) compared to Hookers

§ significantly greater (p<0.001) compared to Locks

θ significantly greater (0.001≤p<0.01) compared to Locks

ω significantly greater (0.01≤p<0.05) compared to Locks

ρ significantly greater (0.001≤p<0.01) compared to Back Row

Π significantly greater (0.01≤p<0.05) compared to Back Row

τ significantly greater (0.001≤p<0.01) compared to Scrum Halves

v significantly greater (0.01≤p<0.05) compared to Scrum Halves

χ significantly greater (0.001≤p<0.01) compared to Out Halves

Ω significantly greater (0.01≤p<0.05) compared to Out Halves

Π significantly greater (0.01≤p<0.05) compared to Centre

σ significantly greater (0.001≤p<0.01) compared to Wingers

Ψ significantly greater (0.01≤p<0.05) compared to Wingers

Δ significantly greater (0.01≤p<0.05) compared to Full Backs

3.5 Discussion

Positional differences in match demands were identified, as hypothesised, with a greater ($p < 0.001$, $d = 0.74$) distance covered for backs (5918 ± 1206 m) compared to forwards (5035 ± 1157 m), in conjunction with the backs playing at a higher intensity (70.9 ± 7.4 m/min) compared to the forwards (64.0 ± 6.3 m/min; $p < 0.001$, $d = 1.00$). As was also hypothesised, forwards experienced a greater number of impacts > Zone 3 (229 ± 160) compared to the backs (226 ± 151), although this was not significantly different ($p > 0.05$, $d = 0.01$). Additionally, it was correctly hypothesised that backs conducted a greater number of accelerations (32.2 ± 10.6) compared to forwards (22.0 ± 11.9 ; $p < 0.001$, $d = 0.88$) and a greater number of decelerations (41.9 ± 12.3) compared to the forwards (30.8 ± 14.4 ; $p < 0.001$, $d = 0.82$).

Within the nine positional groups, differences in match demands were identified, as hypothesised, with a greatest distance covered by full backs (6904 ± 740 m) compared to the lowest being props (4285 ± 893 m) ($p < 0.001$, $d = 3.19$). It was, however, important to note that centres (6043 ± 966 m) covered a greater distance than wingers (5926 ± 1295 m) ($p > 0.05$, $d = 0.10$) and scrum halves (5408 ± 978 m) ($p > 0.05$, $d = 0.65$), unlike what was hypothesised. Additionally, full backs played at the highest intensity (70.9 ± 7.4 m/min) compared to the props (64.0 ± 6.3 m/min) ($p < 0.001$, $d = 1.00$), who played at the lowest intensity, with out halves (71.9 ± 5.1 m/min) surprisingly working at a greater intensity than wingers (69.0 ± 6.4 m/min) ($p > 0.05$, $d = 0.50$), unlike what was hypothesised. Lastly, conflicting with the hypothesis, scrum halves (274 ± 145), hookers (291 ± 145) and full backs (296 ± 99) experienced the highest number of impacts > Zone 3. Back row (225 ± 109) experienced the fifth highest number of impacts > Zone 3 and the fourth most Im6 (67 ± 27), behind full backs (87 ± 27), hookers (80 ± 33) and props (70 ± 74).

Distances covered in this study were lower than presented in previous research (Cahill et al., 2013; Coughlan et al., 2011). Cahill et al. (2013) reported distances of 5850 m and 6545 m for the forwards and backs respectively, while Coughlan et al. (2011) noted distances of 6427 m for the forwards and 7002 m for the backs. The greater distance covered by backs compared to forwards in this study was expected, because backs tend to complete more open field running, as has been reported in previous research (Cahill et al., 2013; Quarrie et al., 2013). When comparing results from the nine positional groups with previous research (Cahill et al., 2013), it was apparent that distances covered across positional groups were lower for all positions except full back. This study showed full backs (6904 ± 740 m) to cover greater distance than that recorded by Cahill et al. (2013) (6489 ± 1572). On further analysis of the full back position, this was the position that recorded the highest mean duration of minutes played within the data set and therefore likely explains the high distances covered compared to the other eight positional groups within this research. The values reported by Cahill et al. (2013), for full backs are likely to be explained by these players playing fewer minutes. However, as Cahill et al. (2013) does not quantify minutes played within their research, this notion is somewhat questionable.

As previously mentioned, since the advent of professionalism the game has become more intense (Quarrie et al., 2013), with one of the consequences being that tactical substitutions are made to ensure that players are fresh to perform their task. Considering the results above, the variations seen in the match characteristic data for this study and that of previous research (Cahill et al., 2013; Coughlan et al., 2011) may be explained by the minutes played by individuals. Coughlan et al. (2011) examined only players who played for 80 minutes and

Cahill et al. (2013) only included players who played longer than the average substitute's game time. It could, however, be argued that this study is perhaps more representative of modern rugby union, where players are often asked to play less than the full match duration, with the reduced volume of playing minutes expected, potentially, to result in a more fast paced and explosive performance. As was noted within this study and the research by Lacome et al. (2015), forwards generally played fewer minutes than backs. Positional groups, especially in the forwards, are often substituted for tactical reasons and it is now commonplace, in many elite teams, to see forwards not playing the full duration of the game. Due to the reduced game time performed by players, positional groups are often conditioned for substitution roles, which appear to involve greater intensity of movements and activities over shorter playing times. Therefore, excluding players who do not play the whole duration of the game is short sighted and does not guide practitioners upon the game demands placed upon specific individuals.

Intensity, in this study, (Forwards 64.0 ± 6.3 m/min and backs 70.9 ± 7.4 m/min) displayed slightly smaller values in comparison to Cahill et al. (2013) (Forwards 64.6 ± 6.3 m/min and backs 71.1 ± 11.7 m/min), with similar findings presented by Coughlan et al. (2011), who reported 66.7 m/min for forwards and 71.9 m/min for backs. This is similar to the research by both Reardon et al. (2015) and Lindsay, Draper, et al. (2015), who noted average intensity of 77 m/min and 81 m/min, respectively. It is, however, important to note that the values from both Reardon et al. (2015) and Lindsay, Draper, et al. (2015), were taken from distance per game time minutes, and therefore possibly account for the higher intensity values displayed. As noted above, individuals who play shorter durations are likely to play with greater intensity than individuals who played for the full 80 minute duration of a match, as pacing strategies would, potentially, not be adopted. This study showed that hookers, locks, wings and full backs played at a higher intensity than that reported by Cahill et al. (2013), yet props, back row, scrum halves, out halves and centres were reported to play at a higher intensity in the study by Cahill et al. (2013). As this study used players who played durations ranging from thirty to eighty minutes, it is surprising that some positional groups' intensity values are smaller when compared to those in previous research (Cahill et al., 2013; Coughlan et al., 2011), particularly as they involved players competing for longer durations. It is, however, important to consider that the study by Coughlan et al. (2011) is taken from international rugby (involving only two subjects), where one would expect a higher average intensity, compared to that of the domestic level professional rugby, as it is considered to be a lower playing level.

On analysis of the distance covered in speed zones it was apparent that backs spent longer in D1 (2195 ± 542 m) and D6 (77 ± 66 m) compared to forwards (D1 1898 ± 450 m; D6 14 ± 19 m), but that forwards (914 ± 264 m) spent longer in D3 compared to backs (904 ± 243 m). A back spending a longer time in both D1 and D6 is not surprising, considering they are required to perform more high intensity movements than forwards and are reported to have longer work to rest ratios than forwards during match play (Austin et al., 2011a). Accelerations and decelerations assessed within this study are also highest amongst backs (Accelerations 32.2 ± 10.6 ; Decelerations 22.0 ± 11.9), compared to forwards (Accelerations 22.0 ± 11.9 ; Decelerations 30.8 ± 14.4), supporting the view that backs work at a higher intensity, but have longer recovery periods between efforts. This notion is further supported when considering the aforementioned distance covered in each distance zone.

As reported by Coughlan et al. (2011), 75% of total rugby union match distance, is performed at low intensity (0-3.6 m/s). This study also shows the majority of match distance covered as

being of low intensity (95%) (D1, D2, D3 and D4) and it is perhaps surprising how little of the actual distance covered is of high intensity (D5 and D6), when comparing values to that of previous research. Practitioners are, however, guided to consider the intensity values with caution as the distance in zone categories within this study differ to that of previous research (Cahill et al., 2013; Coughlan et al., 2011) and in addition the classification of what is regarded high intensity also differs. This research classified high intensity work as movement above 19.8 km/h, whereas the work by Cahill et al. (2013) noted high intensity work at differing values. Cahill et al. (2013) noted that all positions covered at least 80% of their total distance at the following categories <20% Vmax (standing and walking), 20– 50% Vmax (jogging). Also, instead of using distance covered in speed zones to classify low and high intensity work, the authors reported relative speed classifications that were based upon unclassified individual maximum sprint speeds.

On closer examination of the distance covered at high intensity within this study, forwards performed 3% of their distance at high intensity (>D4), while backs performed 6% of their distance at high intensity (>D4). Cahill et al. (2013) noted forwards performed 6% (369 m) of their distance at high intensity (> 81% Vmax), while backs performed 4% (323 m) of their distance at high intensity. This small amount of high intensity work has also been reported within many time-motion analysis studies (Austin et al., 2011a; Deutsch et al., 2007; Quarrie et al., 2013) and GPS studies (Cunniffe et al., 2009), illustrating that rugby union is a sport of intermittent activity with contact situations and high work to rest ratios representing a large proportion of the match demands to which players are exposed to. Within the nine positional groups assessed no clear pattern emerged, with many positions sharing the furthest and shortest values for the distance covered within zones. Scrum halves presented the furthest distance covered in D4 (1009 ± 214 m), which considering their role within the game as the link between the forwards and backs, is perhaps not surprising. They are required to perform many metres at moderate pace and attend every contact situation in order to distribute the ball. Additionally, of note within the distance zones was the data showing that full backs presented the furthest D2 (2078 ± 275 m) and D5 (429 ± 118 m), which signify that full backs are required to cover a vast amount of distance at both low and high intensity, to follow play in the backfield during both attacking and defending situations. Also of interest was the data for centres, which illustrated the significant ($p < 0.001$) amount of time spent in D1 (2405 ± 256 m), where they are most likely to be engaging in contact situations (attacking and defending), as is common within their positional role. This is also evident in the high total number of impacts recorded for centres compared to the other backs (excluding full backs). Lastly, it is of note (Table 3.7) that wingers perform the furthest distance in D6 (139 ± 72 m), which would be expected, considering their physical characteristics and their main role within the team as an attacking threat to score tries, as detailed within the literature review of this research (Table 2.1 and Table 2.11).

As previously mentioned, few earlier studies in rugby union have incorporated GPS data on impacts, meaning that values upon which to draw comparison within this study are limited, therefore adding to the novelty of this study. Cunniffe et al. (2009) revealed that forwards were involved in 60% more high level impacts (> 8 G) than backs, but that backs produced marginally more work than forwards. In the study by Cunniffe et al. (2009) it was also revealed that forwards experience thirteen “severe” impacts (10+ G) per game compared to backs, who were noted to only encounter four “severe” impact instances, although the relevance of this data can be questioned, considering that it was based on only three players. Recent research by

Schoeman et al. (2015), assessing differences between playing position and collision rates within professional rugby union, added to the knowledge of impacts, noting significant differences between forwards and backs regarding collision rates ($p \leq 0.05$). This is in contrast to the results presented within this study, which identify backs as experiencing more collisions. It is, however, important to note that the research by Schoeman et al. (2015) was taken from time-motion analysis and therefore does not identify the magnitude of impacts from GPS analysis (be these impacts from collisions or not). A need for caution when comparing the results from this study to that of any previous, or future, research in the area is, however, advised.

Recent research using GPS methods upon which to compare the frequency of impacts reported within this study does exist (Tee & Coopoo, 2015), where it was revealed that there was no difference in the total number of impacts (> 5 G) experienced by backs (9.5 ± 3.2) or forwards (10.0 ± 3.0) (> 5 G.min⁻¹), or the frequency of high-intensity impacts (> 8 G.min⁻¹) (Backs 1.1 ± 0.4 ; Forwards 1.1 ± 0.5). This is, however, in contrast to the research by Lindsay, Draper, et al. (2015), who noted forwards as experiencing more impacts per minute than backs (0.56 ± 0.23 ; 0.36 ± 0.17). Despite this study showing that backs experienced a greater total number of impacts than forwards (Forwards 3176; Backs 5501), in contrast to their hypothesis, this study does support the view that forwards are involved in more “heavy” impacts ($> \text{Zone } 3$). Impacts < 7 G in this study (Forwards 229 ± 160 ; Backs 226 ± 151) were lower than those reported by Coughlan et al. (2011) (Forwards 670; Backs 466). However, the GPS units used both within this study and that of Coughlan et al. (2011) do vary, therefore potentially explaining the differing results regarding impacts. It is also important to note that forwards experienced a significantly greater number of Im6 when compared to backs ($p < 0.03$), which when considering these Im6 instances represent a 13-15 G involvement, the resultant physical influence this might have upon the players involved is apparent. Further support for the effect of high magnitude impacts upon resultant time-course of recovery post-match play was noted within similar research in rugby league (McLellan et al., 2011a), where it was reported that significant skeletal muscle damage was highly dependent on the number of heavy collisions > 8.1 G, as illustrated by increased CK and C values. Another comparison of interest when assessing similar research is that the accelerometer in the *StatSports* device used within this study classified impacts if they were above the 3 G level, meaning that many so-called “impacts” from match situations were potentially due to movements, rather than physical contact with the opposition or the playing surface. In contrast, Coughlan et al. (2011) reported light impacts as 5.0 – 5.9 G, therefore excluding many impacts which could be accounted for by movement rather than contact. The varying impacts values displayed in this study, could, therefore, be accounted for by the differing classification of impact zones.

Props typically experienced the lowest number of impacts in the lower impact zones (Im1, Im2 and Im3), yet experienced a large number of impacts in the higher impacts zones (Im4, Im5 and Im6), when compared to other positions (locks, scrum half and out half). The results from this study, therefore, differ from that of Schoeman et al. (2015), who noted props and locks experiencing similar collision rates (Props $p = 0.07$; Locks $p = 0.62$). However, as noted above the research by Schoeman et al. (2015) was taken from time-motion analysis research and not GPS assessment, meaning that comparisons should be cautioned against. Full backs showed a significant level of impacts on both low ($p < 0.001$) and high impact zones ($p = 0.006$), yet the positions of props, hookers and back row illustrated high Im6 values when compared to the values they experienced at the lower impact zones. It is important for practitioners to note,

that, as hypothesised, this research does not support the view that props, hookers and locks experience the largest number of high magnitude impacts. However, the duration of minutes played by each position should be considered before comparison is made.

A new finding of this research is the total number of impacts and the wide range of impacts experienced by full backs. It is, however, important for practitioners to note that the high number of low level impacts, could perhaps be explained by the distance, speeds and intensity at which full backs are required to work, as evidenced within this study by the amount of time full backs spend in all speed zones. The low level impacts assigned to Zones 1m1, 1m2 and 1m3 are most likely to be collected by the GPS unit during locomotive tasks, rather than during contact situations (with the opposition and the ground) meaning that 1m1, 1m2 and 1m3 do not provide a true reflection of player impact load experienced via contact. However, the number of high level impacts (1m6) for full backs is a new finding from this study, which although caution still needs to be considered when comparing positions within this research, is an area of potential future investigation. Prior research (Tee & Coopoo, 2015) has also reported that outside backs (1.2 ± 0.4 , ES 0.2 - 1.4) were the positions most likely to be involved in high-intensity impacts ($> 8 \text{ G}\cdot\text{min}^{-1}$) and the results from this experimental study would support this. When considering that outside backs are capable of performing high-speed movements, resulting in a preponderance of high-speed collisions, these findings are not unexpected. The distances covered within this experimental study are not surprising, considering those presented in prior research outlined in the Chapter 1 (Austin et al., 2011a; Cahill et al., 2013; Cunniffe et al., 2009; Jones et al., 2015; Lindsay, Draper, et al., 2015; Venter et al., 2011). Importantly, however, high intensity effort, such as the frequency of accelerations, decelerations and impacts with their likely influence they upon restoration of performance, should be a consideration for future research.

Future investigation of GPS impacts data perhaps needs to assess critically and in more detail the exact load being placed upon players during impacts, with the aim of classifying them into "heavy" and "very heavy" values as outlined by Coughlan et al. (2011). Additionally, the incorporation of video analysis alongside GPS data would better inform practitioners upon which movement or match involvement is eliciting these impacts. As explained above, many of the impacts experienced by some positional groups, within this research, may have been as a result of varying match demands (landing from jumps, changing direction or skill involvements) and not solely from collision contacts with the opposition. This further level of impacts analysis would help guide practitioners on the magnitude of impacts and the effect these impacts have upon players. Baseline values of the amount of impacts experienced by positional groups (props, locks) and the magnitude of these impacts may aid future prescription of positional specific training programmes for rugby union players. Although this study does not investigate the number of contact situations (scrum, ruck, tackle and maul) experienced by players during games of rugby union, one could argue that that the contact elements of rugby union are so intense that, although small in actual number, are high in overall load upon players. Despite the effect that contact situations analysis could have upon the results from this study, the complexity of assessing static exertions meant that this research only assessed the dynamic involvements of match play and impacts classified from GPS. Load analysis, assessing contact situation involvement, would require time-motion analysis research, as seen in the study by Schoeman et al. (2015) assessing collision rates. The combination of time-motion analysis with GPS data would provide a greater level of detail regarding contact load, which is, therefore, a further potential area of future development.

From this research it is clear that backs perform at a higher relative intensity than forwards and that backs compete over a longer time period than forwards. The greater intensity to which backs are exposed would likely have an effect upon their neuromuscular performance post-match, as supported by the aforementioned research of McLellan et al. (2011b). Despite forwards experiencing only a slightly higher number of impacts > Zone 3 compared to backs, the impacts they experience are most likely to be a result of the greater volume of contact situations, rather than from the jumping and landing impact tasks that the backs experience. The impacts experienced by forwards compared to backs are likely to add significant fatigue and neuromuscular response to forwards' post-match. This notion is supported by previous research by Duthie et al. (2006), who noted that sprinting represents 4% of the game movements for the forwards and 25% for the backs, yet the relative effect that sprints have upon fatigue, compared to that experienced as a result of collisions, could be questioned. The questionable effects on fatigue of distance covered and neuromuscular response post-match, is, perhaps, an area practitioners should focus upon, with relative intensity and relative impacts (impacts per minute) used as possible guidelines for judging the load exerted upon rugby union players during matches.

This greater number of impacts experienced by positional groups, within both previous research and this study, was noted as important for future consideration by Quarrie et al. (2013), where forwards require a longer time to recovery, due to the greater contact load experienced. The effect that this larger volume of impacts has on forwards, in contrast to backs, is another possible area of investigation for the future, where muscle soreness post-match in forwards is often the consequence. It could also be important to consider backs' muscle soreness, in contrast to forwards', who despite completing greater match distances, are exposed to a lower number of impacts. This lower level of match impacts for backs, may mean that they have more opportunities for passive recovery while they walk or jog between plays. This longer time between efforts, therefore, potentially enables creatine kinase clearance, subsequently enhancing recovery (Cunniffe et al., 2009). These resultant movement patterns and time to work ratios for positional groups could perhaps further explain the differences seen in muscle soreness post-match and therefore could aid practitioners in prescribing future training programmes. Performance testing is now commonplace in many rugby union settings, yet GPS data should be the mainstay upon which to compare testing data in the days post-match. Data from this study, showing forwards covering less distance and experiencing more impacts than backs, provides further support for position specific conditioning programmes, with recommendations for coaches regarding match demands. Future planning is recommended for coaches, where training prescription can be based upon a player's recent training history, comparing previous training cycles to concurrent data and the match demands presented.

3.5.1 Limitations of this study

All of the variables reported within this research represent absolute values (excluding intensity), making the relevance of comparing the nine positional groups somewhat questionable. As previously argued, analysing data from players who played between 30 and 80 minutes, adds weight to the novelty and rationale for this research. However, comparing and contrasting positions is cautioned against. Instead practitioners should perhaps consider relative data (variable per minute) for some of the match demands assessed in order to obtain a true representation of position comparisons. Practitioners are, therefore, advised to conduct further research into the comparison of absolute and relative methods of match demands

analysis. Relative data will aid in identifying why differences might occur between positions, while absolute values are useful in understanding the real demands of each position, as they record what the players suffer as a total load throughout the match. Absolute values are, therefore, an important consideration and as such should not be discounted. For example a player might perform at a high intensity (variable per minute) during their time on the field, yet if their minutes on the field are small, the relative values they experience are perhaps not as important for consideration when compared to another player who has played the full duration of the game. A player who plays the full duration of the game is likely to have lower relative values across many match demands, yet also likely to have very high absolute values, therefore warranting consideration within post match analysis.

When considering the claim above that both absolute and relative measures are of interest, it is potentially also important for practitioners to consider analysis to be position related. The relative values for forwards are perhaps of more interest than the backs when assessing the data above in Tables 3.4-3.9. Some variables might present more information from a relative view, rather than an absolute, considering the reduced minutes played by many of the positions within the forwards, compared to those of the backs. Despite no data existing to show the reduced minutes played by forwards in comparison to backs across many leagues and teams, this view is considered “real world”. The playing positions that experience bouts of impacts within a shorter period of time (impacts per minute) are perhaps better assessed from a relative view, with the resultant effect of clustered impact bouts upon restoration of performance post-match warranting future investigation. However, an individual that plays 29 minutes could in fact be exposed to a large match demand and the procedure for inclusion within this research would not allow such examples thus limiting analysis potential. A “cut off” point, nevertheless, had to be set to ensure clarity and avoid unstructured data collection.

As a result of the data within this research being provided by only one team over the period of a playing season, it could be argued that this data does not present a full picture of the match demands of players within the northern hemisphere, instead only representing the match demands for the team in question. Playing styles, tactics and league position could all be major factors in the minutes played by positional groups within this team and in the tasks that they are asked to perform. Additionally, it is important for practitioners to note that differences in findings between studies (Austin et al., 2011a; Cahill et al., 2013; Coughlan et al., 2011) might, in part, be due to the contrasting styles of play between northern and southern hemisphere teams, as impacted by weather conditions, referee interpretation and strength and conditioning practices (Jones, Smith, Macnaughton, & French, 2017). Despite the data collected adding to the knowledge of match demands within rugby union in the northern hemisphere, the limitation of using data from only one team only is a point for practitioners to consider when they are examining the results. One potential way of overcoming sample size and “one team” limitations is to combine data from multiple teams, similarly to the research of Cahill et al. (2013). However, the element of direct competition, inherent in European team games, means that sharing of data is and will continue to be unlikely.

Differences in methodology are also a point to consider, as some previous studies utilised GPS to measure movement, while others solely used time-motion analysis methods from video review. Considering that both the studies by Coughlan et al. (2011) and Cahill et al. (2013) used 5 Hz GPS units, in comparison to the 10 Hz units used in this study, this is a major point of consideration when comparing GPS data. As was illustrated by Johnston, Watsford, et al. (2014), 10 Hz GPS units are more reliable than 5 Hz GPS units and therefore are recommended

for use in future research. Another possible explanation for the differences in data is that rugby union in the professional era is getting faster. Evidence for evolving match characteristics is illustrated by Roberts et al. (2008) who found that the average number of sprints during a game was 20. This is in contrast to data from Austin et al. (2011a) showing an average of 40 sprints across all playing positions. The disparities in GPS values, seen in this study and similar research by Twist et al. (2014) between northern and southern hemisphere, does, however, add ecological validity to the current body of research.

3.6 Practical Applications

The data from this study adds to the knowledge of what are typical match characteristics for professional rugby union in the northern hemisphere, helping guide practitioners to assess the match demands required for positional groups. Based upon the results of this study, coaches will be more informed upon what each positional group is required to complete within an elite team's match situations. The ability of coaches to make decisions upon whether an individual player can perform a specific role for the team is important for future practice. When new match characteristic data is collected it can be compared against previous match data and the potential neuromuscular effect that games might have had on the individual players can be assessed.

When assessing the demands of the sport, specific training recommendations that should be considered for elite level rugby union, are, firstly that high levels of aerobic fitness are required to complete the distances noted within this research. Secondly, that high muscle mass and strength are required to cope with the impacts illustrated within this study. The aerobic fitness and ability to withstand impact forces vary across all nine positional groups, yet the need for both of these components of physical preparedness is evident from the data collated. As a result of this study, it could be concluded that the physical stature of each positional group guides the match demands expected and that aerobic fitness and strength programming should, therefore, be prescribed relative to position. Additionally, from match characteristic comparison, future planning can be implemented into strength and conditioning programmes in order to improve individual readiness to train in the days post-match.

Lastly, as mentioned previously, a combination of video analysis with GPS data would help guide practitioners on the nature of the impacts experienced within match situations. A deeper level of assessment is needed, when considering that the results from this research show the high level of impacts experienced by positions such as full back. Despite backs experiencing a greater number of impacts, many of these impacts are likely not to be from collisions and could, as a result of the match demands conducted, result in a different neuromuscular response.

3.7 Implications of experimental chapter 3 for subsequent studies

Now that match characteristics have been identified, a need exists to identify a performance measures that will be able to assess rugby player fatigue in the days post-match. As illustrated in the review of literature, jump testing is perhaps the most realistic performance measure for use in the applied context within which this series of investigations occur. The following experimental chapter therefore aims to assess the reliability of multiple jump modalities, to ascertain which is the most applicable for use within assessments of match fatigue. Additionally, the likely restoration of performance experimental chapters that will follow this jump reliability study, need to involve assessment of match characteristics data, therefore further supporting the completion of match characteristic assessment within this thesis.

4 Within and Between-Session Reliability of Jump Performance in Elite Rugby Union Players

4.1 Abstract

CMJ testing is commonly used within elite field sport settings to assess NMF. This study assessed the within and between-session reliability of three jump-tests, including CMJ, SJ, single leg drop jump left leg (SLDJ-L) and single leg drop jump right leg (SLDJ-R), to determine which jump protocol was most reliable and reported on their resultant measurement error.

Participants completed two trials of each jump during each session, on three occasions. Within-session reliability was determined via intraclass correlation coefficients (ICC) and between-session reliability determined using both ICC and repeated measures ANOVA, with Bonferroni post-hoc analysis, or non-parametric equivalent, used to check for learning effects. Reliability within-session for CMJ, SJ and SLDJ-L (ICC 0.938, ICC 0.954 and 0.759 respectively) jump height, demonstrated high reliability, while SLDJ-R jump height showed low reliability (ICC 0.445). Between-sessions CMJ and SJ showed high reliability, including trivial to small effect sizes (CMJ ICC = 0.906; SJ ICC = 0.866), with no significant differences ($p > 0.05$) in jump height observed between days. Between-sessions reliability for SLDJ jump height showed high reliability for left leg (ICC = 0.875) and moderate reliability for the right leg (ICC = 0.759), with a small effect size between sessions for the left leg and trivial effect size for the right leg, yet both were non-significant ($p > 0.05$) between days. This study illustrates that CMJ jump height represents high reliability both within and between-session across all three testing days, in contrast to the SJ, SLDJ-L and SLDJ-R. Findings also show that CMJ demonstrates the lowest SDD (1.7%) between sessions. When comparing unilateral jumps to bilateral jumps, it was clear that CMJ provides the most sensitive and reliable data, therefore it is suggested that unilateral jumps should not be used as a performance indicator, due to lower reliability. In addition, practitioners should consider a change in jump height of $\geq 1.7\%$ as meaningful, when assessing elite rugby union players performing CMJ.

4.2 Introduction

The vertical jump has long been used as a method of assessing lower limb power and has been reported to possess sensitivity in tracking training induced changes for peak power output and rate of force development (Carlock et al., 2004; McLellan et al., 2011d). Jumping in general, is one of the most prevalent acts performed in sport (Markovic et al., 2004), with athletes in many sports often required to jump in order to perform their role in a team game or an athletic task; including jumping to intercept a ball in football or jumping to avoid an obstacle in athletics. Research by Bosco et al. (1987) noted performance qualities of jumping and running to be similar in nature, with vertical jump, therefore, highly relevant for assessing sporting performance, where a large running element exists. Approximately 500 ground impacts have been reported to occur in rugby match situations, with many of these likely to be from jumping actions (Cadore et al., 2013; Sheppard, Gabbett, & Stanganelli, 2009). Many of the jumping aspects of game movement in team sports appear at important moments in the game, often in order to contest possession and likely to be critical moments in game outcome. Activities that do not involve jumping, such as tackling in rugby, also utilise power elements, upon which an effective measurement of power is required when monitoring the athlete's development (Klavara, 2000).

An individual's ability to generate force quickly is a key performance measurement for athletes competing in many team sports, hence jump tests have been utilised to monitor power and the effects of training and for talent selection purposes (Markovic et al., 2004). When measuring jump performance, the goal of many practitioners is to measure jump height, with the role of power within this measure being interrelated. However, as reported by Winter et al. (2016), the use of the term "power" is often misplaced. Power is the product of force and velocity, with power described as the rate of work or the force multiplied by the velocity of movement (Kawamori & Haff, 2004). Within the context of jump performance testing, it is essential that practitioners understand the relationship between jump height and power, as one is not a direct measure of the other. In essence, jump height is commonly used as a proxy for power, yet the understanding of the difference between these two measures is key. In their review of mechanical terms commonly used in sport and exercise research, Winter et al. (2016) recommended the use of the term "intensity" alongside the appropriate unit measurement when discussing power elements, to best describe the specific kind of exercise performed.

With the goal of assessing lower limb jumping ability, many jump tests, including vertical jump, have been developed. Vertical jump is perhaps the most commonly reported jump modality, yet many similar jump tests commonly used in the applied setting include CMJ and SJ. The vertical jump has been also been reported to represent an inaccurate measure of explosive lower limb power, when arm swing is permitted, due to the more complex nature of leg and arm coordination (Leard et al., 2007; Markovic et al., 2004; Young et al., 1997). Lees et al. (2006) concluded that arm swing contributes to jump performance by aiding the storing and release of energy from muscles and tendons around the ankle, knee and hip and by initiating a pull force at the shoulder joint thereby increasing jump height by 10% or more (Lees et al., 2004). Harman (1990) reported that this increase in jump height is not due to upward acceleration of the arms seen during the jump, but by the force velocity relationship of the muscle contraction. Simultaneously the upward acceleration of the arms creates a downward force on the rest of the body, slowing the contraction of the quadriceps and gluteal muscles, so that more force can be exerted. Due to the above effects regarding variability of vertical jumps (using arm action), this type of jump assessment has generally been excluded from recent research (Acero et al., 2012), with bilateral jump performances commonly being conducted with hands on hips or holding a bar on the shoulders to minimise variability.

Research by Harman et al. (1990) reported that unilateral jump performance had a stronger relationship with sprint performance than a bilateral jump. Despite recent jump testing investigations focusing solely on the SJ and CMJ and not unilateral derivatives (Gallardo-Fuentes et al., 2016; Gathercole, Sporer, & Stellingwerff, 2015; McMahon, Murphy, Rej, & Comfort, 2016; Till, Jones, Darrall-Jones, Emmonds, & Cooke, 2015; West et al., 2014), the use of unilateral derivatives should not be discounted, as many movements associated with team sport play are conducted on one leg and therefore the validity of unilateral testing is warranted. When considering that unilateral jumping is a typical plyometric exercise, widely used as an effective training method (Young, MacDonald, & Flowers, 2001) and considered to be a faster stretch shortening cycle movement than the CMJ, its need for future investigation is further emphasised.

In addition to using jump tests to measure lower limb jumping ability, recent research (Cormack et al., 2013; Cormack et al., 2014; Hamilton, 2009; McLellan & Lovell, 2012; McLellan et al., 2011a, 2011b; Taylor, 2012) has focused on utilising vertical jumps with a standardised

protocol to assess NMF, as discussed in Chapter 2.3.3. A recent study in elite rugby league, found that CMJ performance was impaired for up to 24 hours post-match, reporting a 26% reduction in PRFD 24 hours post-match (McLellan et al., 2011a, 2011b, 2011c, 2011d; Twist et al., 2012). As seen in the study by McLellan et al. (2011a), PRFD on average was $12653\text{N}\cdot\text{s}^{-1}$ across rugby league players 24 hours before the game and on average $9379\text{N}\cdot\text{s}^{-1}$ 24 hours post-match. Additionally, another study on rugby league players (McLean et al., 2010) reported that CMJ flight time and relative power were significantly reduced in the 48 hours following the match. Moreover, McLean et al. (2010) reported that CMJ variables returned to near baseline values four days after matches. The ability to assess NMF will provide a better understanding of athletes' readiness to train and the possible foresight to alter their training load based upon data. It is, however, important for practitioners to note that an instant measure of NMF is often required in elite team sport settings, meaning that the investigation of kinetic measures may be discounted in favour of a more instantaneous measure, such as jump height.

When using force plates, the inability to test on a sport specific surfaces is considered a disadvantage, yet the many advantages of force plates outweigh the disadvantages and they are therefore considered to be the "gold standard" instrument for jump assessment (Casartelli et al., 2010). Optical measuring systems (infrared mats) have also been critically analysed (Glatthorn et al., 2011). The *OptoJump* system (Microgate, Bolzano, Italy), which consists of one receiver and one transmitter bar was shown to have excellent reliability (Glatthorn et al., 2011) with recommendations to use *OptoJump* and force plate (Quattro Jump, Kistler, Winterthur, Switzerland) interchangeably (Bosquet et al., 2009). Glatthorn (2011) reported intraclass correlation coefficients (ICCs) for reliability of 0.997–0.998, despite a systematic difference in jump height between force plate and *OptoJump* (2.5%; $p = 0.001$). The main benefit of the *OptoJump* optical timing system is that it allows subjects to be assessed for jump tests on the same surface upon which they would perform during their sporting activity. Caution was, however, advised when using optical devices' such as *OptoJump* as misalignment of photoelectric cells can cause discrepancies in results. A more recent study by Castagna et al. (2013) reported a significant difference in two portable devices (*OptoJump* and *MyoTest*), assessing CMJ flight times, compared to that collected via a force plate. One of these portable devices (*OptoJump*) showed a significantly lower flight time than that recorded on a force plate, further emphasising the need for future study into the validity and reliability of jump testing instruments. In a study by Castagna et al. (2013), assessing validity of vertical jump performance assessment systems, it was stated that the *OptoJump* was considered to be more accurate and reliable than the *MyoTest* (Sion, Switzerland), which utilised a body accelerometer attached to participants waist. In conclusion, Castagna et al. (2013, p. 766) agreed with the work of Bosquet et al. (2009), stating that the "*OptoJump* was a valid and accurate method of assessing flight time when a force plate is not available". Alongside the reported high reliability of *OptoJump* and perhaps of most importance in supporting its future investigation, is the notion that this instrument is more cost effective than a force plate. This means that the likelihood of continued use in many sporting settings is improved.

This study aimed to assess the reproducibility, of the performance of three jump-testing protocols (CMJ, SJ, SLDJ-L and SLDJ-R) assessing jump height on an *OptoJump*, both within and between sessions. The assessment of jump height was considered to be of importance; as time restrictions in many elite team sport settings discount the assessment of more labour intensive kinetic measures. Similarly, the assessment of an *OptoJump* was required, as the cost implications of force plate use outweigh its advantages for many sport settings. Lastly, the

assessment of both bilateral and unilateral jump was considered necessary, when considering that many rugby union match play activities are not always performed from two feet. Results from this study will inform practitioners about which jump protocol is most reliable and the resultant measurement error of each method, while assessing an individual's ability to replicate performance. It was hypothesised that the CMJ would be the most reliable jump modality for within and between-sessions performances, as, firstly, it is the jump method that was most commonly performed by the test subjects, and secondly, CMJ is the jump method that is least likely to carry a variability of technique adopted, when compared to SJ and SLDJ, which perhaps require more coach instruction and familiarisation.

4.3 Materials and methods

4.3.1 Participants

Eight elite rugby union players (age 21.0 ± 4.4 years, height 185.0 ± 8.0 cm, mass 90.0 ± 8.2 kg) from the same professional rugby club volunteered for the study. Participants were all healthy and active individuals who had no current injury issues. All subjects provided written informed consent to participate and Salford University Research and Ethics Committee approved the study.

4.3.2 Jumps

Three types of jump were tested within this study, with two repetitions of each jump performed on three separate days. Participants were asked to standardise activity levels and dietary intake for the 24 hours prior to testing. The jumps performed included a CMJ, a SJ and a SLDJ. Prior to testing, participants engaged in two familiarisation sessions to ensure that techniques were appropriate and standardised. Participants placed their hands on the hips, for all jumps, to eliminate contribution of arm movement (Taylor, 2012). This was also the method to which all participants were accustomed during regular testing in their sporting environment. In line with previous studies, assessing CMJ and SJ performance, protocols such as hands on the hips throughout the jump and extended legs throughout flight to prevent tucking of the knees, (which had been reported to cause inaccuracies) were implemented (Flanagan, Ebben, & Jensen, 2008; Taylor, 2012). Prior to performing the jumps, subjects were asked to perform five minutes of stationary cycling and two minutes of prescribed dynamic stretching.

4.3.2.1 Countermovement Jump (CMJ) technique

The CMJ was performed from a standing position, with the whole plantar part of the foot touching the jumping surface and the hands resting on the hips. A counter movement was conducted by the participants until the knee angle reached approximately 90° , then immediately the participants jumped as high as they could, with their legs remaining straight upon flight, therefore preventing any tucked legs which would lead to inaccurate measurement. Upon landing the participants made contact with the testing surface with knees extended, only flexing to absorb the impact once contact had been made with the floor. Participants were encouraged to jump as high as possible, prior to each jump, with all participants receiving verbal feedback about their performance after each jump.

4.3.2.2 Squat Jump (SJ) technique

The participants had hands on their hips throughout the SJ, and when cued the participants moved from a tall standing starting position into a semi squat position, which they held for three seconds before commencing their jump. After the jump participants received verbal feedback about their performance and were encouraged to jump as high as possible, with no

countermovement jump made at the start of the jump, as identified from visual inspection of the force-time data. If countermovement occurred, participants rested for a further 60 seconds and then repeated the attempt. Previous research by La Torre et al. (2010) assessing the effect of starting knee angle during SJ showed that an increase height, peak force, and maximal velocity may occur as a result of angle amplitude. The notion of knee angle was therefore considered within this testing protocol, with an angle of greater than 90° recommended in accordance with the research by La Torre et al. (2010).

4.3.2.3 Single Leg Drop Jumps (SLDJ) technique

Participants were instructed to place hands on the hips throughout the SLDJ and instructed to “jump for height” when landing in the area directly below the raised starting box position. The box that the subjects started on for the SLDJ was 30 cm high and the box the subjects finished on was 14 cm above the floor where the lasers lay, enabling them to perform correctly this unilateral movement.

4.3.3 Procedure

Despite the testing being conducted post-match, the time-points of assessment were consistent throughout this study and the training and match protocol prior to testing commencing on each occasion was standardised. In addition, the players tested within this study were accustomed to games, as this testing was conducted during the competitive phase of the players’ season, meaning no differing effects of game fatigue could have altered results between weeks. The order of the jumps was standardised, to minimise the effect of fatigue or order during subsequent testing sessions, with one-minute rest intervals between jumps allowing restoration of the phosphagen system to ensure maximal effort. As the unilateral jump involved the most eccentric forces, SLDJ’s were performed last. SJ and CMJ were performed first and second respectively, as they were deemed less fatiguing and are bilateral in nature, providing a natural progression towards unilateral jumps. The CMJ was seen as a good progression from the SJ, hence it was the second jump to be performed. Additionally, in accordance with previous research, it was thought that the order detailed above for these jumps could potentiate each jump (Harman et al., 1990), giving maximal results. Possible potentiation within this study, however, was not considered to be of particular concern, as the jumps used were commonly performed by the elite athletes participating and despite the order being standardised, a protocol of jump technique and the activities performed in the days prior to testing was replicated throughout.

4.3.3.1 Instrument

The instrument used within this research to assess jump height was the *OptoJump* (Microgate, Bolzano, Italy), which was shown to have excellent reliability (Glatthorn et al., 2011), with recommendations for the use of flight time previously reported (Cormack, Newton, McGuigan, & Doyle, 2008) and used in previous research (Buchheit et al., 2008). An *OptoJump* is described as an optical measuring system consisting of transmitting and receiving bars containing light Emitting Diodes (LED), which communicate with each other. *OptoJump* systems are presently used by many elite sports teams, making it possible to measure flight and contact times with an accuracy of 1/1000 of a second. The *OptoJump* was placed on the gym floor, with one box either end of the *OptoJump* to enable performance of the SLDJ. The sampling frequency was 1000 Hz and the sensors were located 3 mm from the testing surface upon which the *OptoJump* bars were placed. The *OptoJump* was 1 m in length with spacing between sensors being 1.041cm apart, meaning that there were 96 sensors per metre of *OptoJump*.

4.3.3.2 Jump Height and Flight time

Jump height was calculated via flight time using the following equation utilised by McMahon et al. (2015) and adapted from that proposed by Bosco et al. (1983).

$$\text{Jump Height} = (9.81 \text{ m.s}^{-2} \times \text{flight time}^2) / 8$$

To ensure accuracy and reliability, participants used a consistent landing technique on CMJ and SJ, where the legs and hips are extended until contact was made with the floor. Flexing of the knees or the hips delays contact with the mat and therefore distorts flight time.

4.3.4 Statistical Analyses

All statistical analysis was conducted on SPSS for windows, with an *a priori* alpha level set at $p < 0.05$. Within-session reliability was tested via intraclass correlation coefficients (ICC) (Model 3, 1). Between-session reliability was determined using both ICC and RMANOVA with Bonferroni post-hoc analysis, or non-parametric equivalent, assessing learning effects. Partial eta squared was reported as recommended by Cohen (1988) and calculated to see if there were any meaningful differences between testing days. Despite the sample population being elite and therefore difficult to recruit for, the low sample size ($n = 8$) involved in this study meant that effect sizes were calculated. In accordance with the views of Buchheit (2016), the sole use of p values should be discounted against as they are sample size dependant. Effect sizes (ES) were also determined using the Cohens d method, and interpreted based upon the criteria suggested by Rhea (2004) and interpreted as follows; trivial = < 0.25 , small = $0.25 - 0.5$, moderate = $0.50 - 1.0$ and large > 1.0 . Post-hoc statistical power was calculated using G Power 3.1 (Faul et al., 2009), for a large effect size of 0.5, a total $n = 8$ was sufficient to deliver an actual power of 0.76. The reliability was considered acceptable if the ICC $r \geq 0.8$ (Cortina, 1993). SEM and smallest detectable differences (SDD) were calculated to provide information upon whether a change in an individual's performance is significant, with SEM calculated using the formula: $SD(\text{pooled}) * (\sqrt{1 - ICC})$ and SDD calculated from the formula: $((1.96 * (\sqrt{2}))) * SEM$. Limits of agreement were represented using Bland-Altman plots within sessions for day one of testing.

4.4 Results

4.4.1 Within-session variability and reliability

Table 4.1: Descriptive (mean \pm standard deviations) and reliability statistics, within testing days for jump height for CMJ, SJ and SLDJ

Leg	Trial 1 (cm)	Trial 2 (cm)	ICC	SEM (cm)	SDD (cm)
CMJ	39.40 \pm 3.40	39.32 \pm 2.94	0.938*	0.17	0.49 (1.3%)
SJ	35.10 \pm 3.81	34.75 \pm 3.79	0.954*	0.23	0.65 (1.9%)
SLDJ	Left	22.70 \pm 3.05	0.759	0.36	1.01 (4.4%)
	Right	23.96 \pm 2.89	0.445	0.42	1.17 (5.0%)
*Reliability significant ($p < 0.001$)					

Within-session reliability for CMJ height demonstrated high reliability (Table 4.1), which is also illustrated within Figure 4.1, with similar reliability for SJ performance (Table 4.1, Figure 4.2).

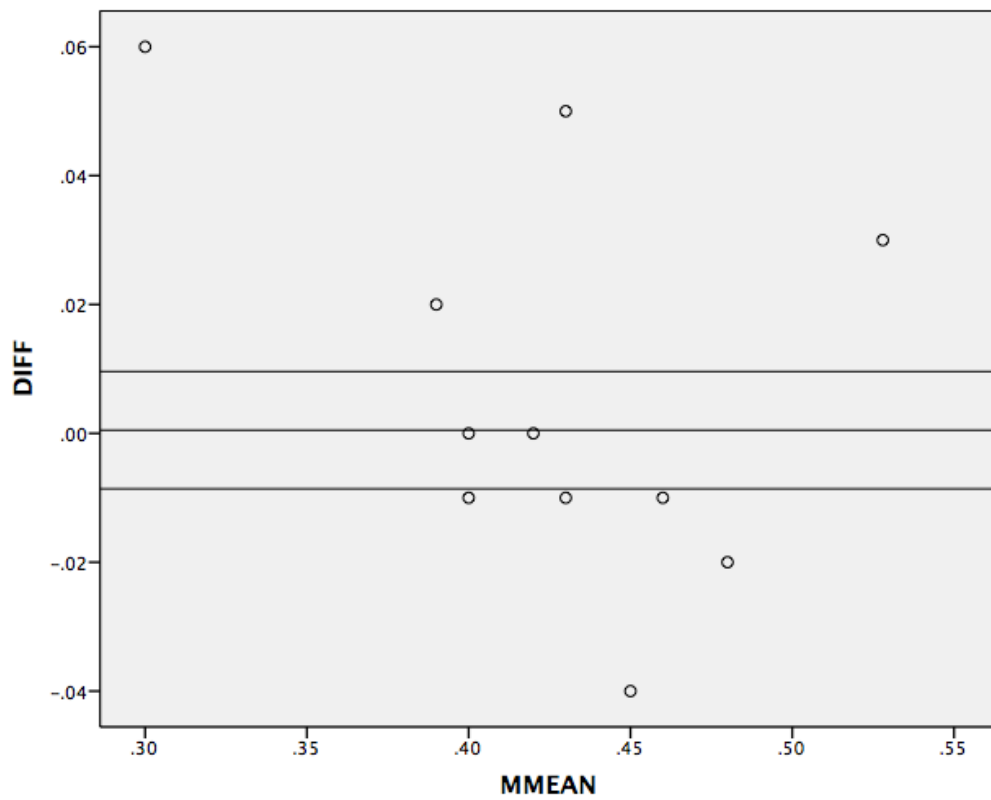


Figure 4.1: Bland-Altman plot for CMJ within session one

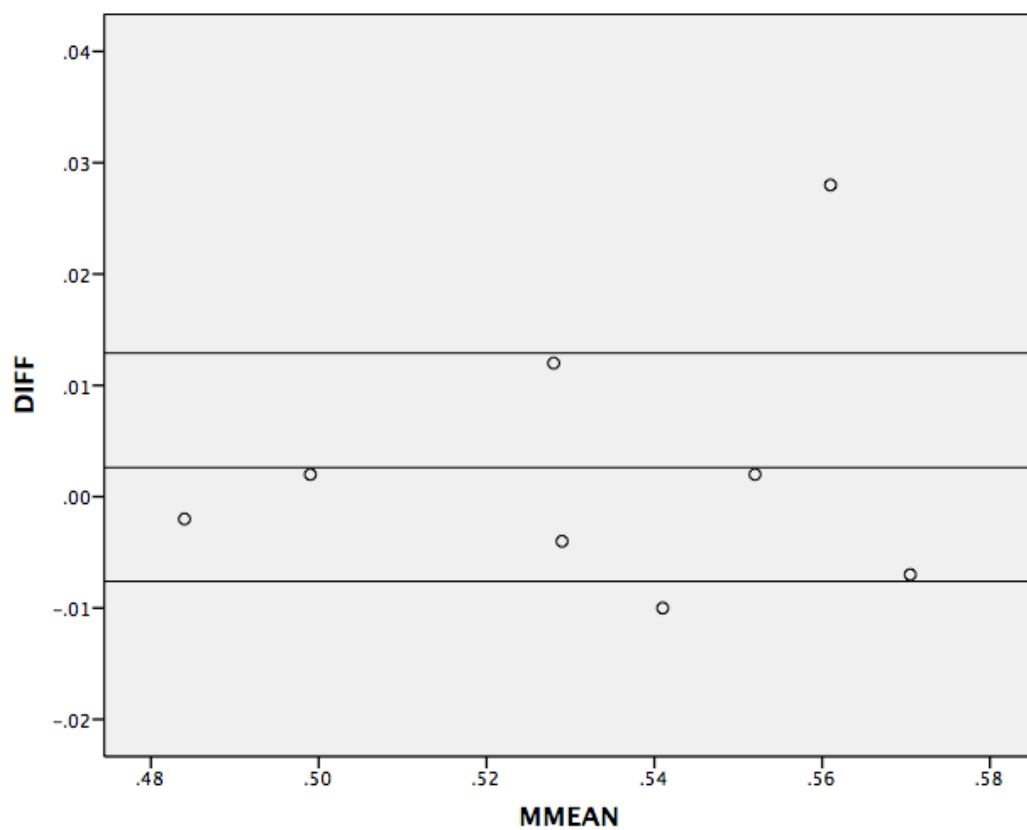


Figure 4.2: Bland-Altman plot for SJ within session one

Within-session SLDJ performance demonstrated moderate reliability (Table 4.1), which is also illustrated within Figure 4.3. Right leg performances showed low reliability (Table 4.1), which is also illustrated within Figure 4.4.

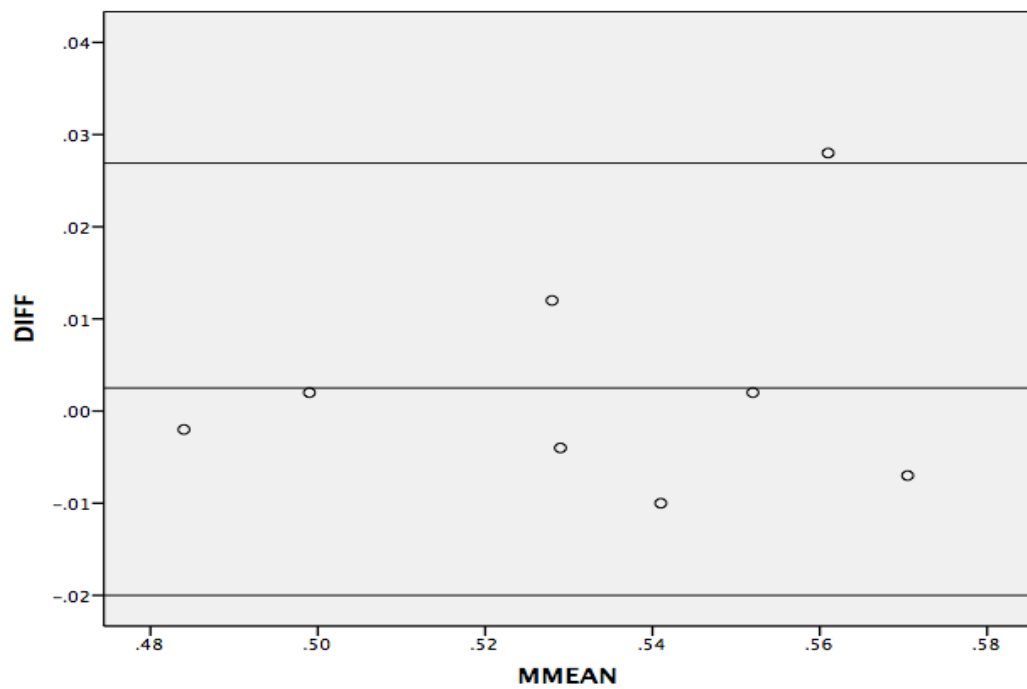


Figure 4.3: Bland-Altman plot for SLDJL within session one

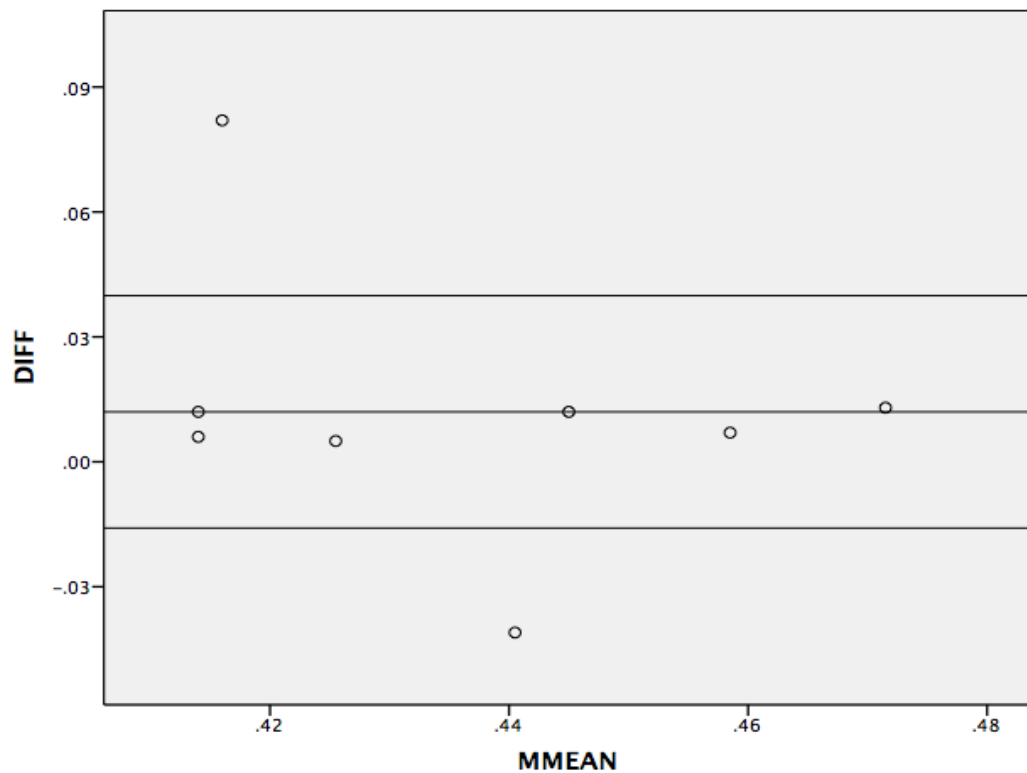


Figure 4.4: Bland-Altman plot for SLDJR within session one

4.4.2 Between-session

Between-session reliability was high for the CMJ, yet significant differences were noted between testing days one and two (Table 4.2). Between-session reliability in the SJ showed high reliability, with trivial and non-significant difference between days (Table 4.2). SLDJ also showed moderate reliability for both left leg and the right leg, with small to trivial effect sizes that were non-significant between days (Table 4.2).

Table 4.2: Descriptive (mean \pm standard deviations) and reliability statistics, between testing days for CMJ, SJ and SLDJ

Jump		Day 1 (cm)	Day 2 (cm)	Day 3 (cm)	ICC r	Partial eta squared	SEM (cm)	SDD (cm)
CMJ		39.96 ± 3.04	37.91* ± 2.90	38.73 ± 3.69	0.906	0.329	0.23	0.65 (1.7%)
SJ		35.49 ± 4.21	37.21 ± 3.73	35.80 ± 3.56	0.866	0.171	0.39	1.08 (3.0%)
SLDJ	Left	24.26 ± 2.95	23.51 ± 4.62	21.58 ± 4.01	0.875	0.321	0.39	1.09 (4.8%)
	Right	24.53 ± 2.44	23.63 ± 5.25	19.42 ± 4.36	0.759	0.199	0.65	1.80 (7.9%)
* Statistical significance between testing days one and two								

The SLDJ-R showed the largest SDD (7.9%), with the lowest SDD being observed in the CMJ (1.7%).

4.5 Discussion

The results of this study are in line with the hypothesis, showing that the CMJ demonstrates the highest reliability within and between sessions, when compared to SJ and SLDJ. CMJ also resulted in the lowest SDD within (1.3%) and between sessions (1.7%), with significant differences noted between session one and session two, although no statistically significant differences were observed between session two and session three. Despite SLDJ-L, SLDJ-R and the SJ showing moderate reliability, the SDDs for these tasks were higher than the CMJ, ranging from 3.0-7.9% between sessions, therefore further supporting the hypothesis that bilateral jumps are more reliable than unilateral jumps.

4.5.1 Within-session

Bilateral jumps resulted in the most reliable performances within sessions (Table 4.1). Reliability of SLDJ within-session was considered unacceptable (ICC $r < 0.8$), for both left and right leg (Table 4.1). The highest within-session reliability was observed during the SJ ($r = 0.954$), with the CMJ providing the second most reliable measure ($r = 0.938$). The higher reliability within-session for bilateral jumps, when compared to unilateral jumps, is likely due to bilateral jump requiring less variation in technique adopted and by these jumps being easier to perform. These results are consistent with other research (Bosquet et al., 2009; Glatthorn et al., 2011), which showed that bilateral jumps using an optical measuring systems are reliable and demonstrates that the athletes can reliably replicate CMJ and SJ performances.

4.5.2 Between-session

Between-session reliability followed a similar pattern to the within-session data, yet CMJ appeared as the most reliable ($r = 0.906$), with significant differences noted between session one and session two, although no statistically significant differences were observed between session two and session three. Between sessions, the SLDJ-R was considered unreliable ($r =$

0.759), yet SLDJ-L was considered reliable ($r = 0.875$) (Table 4.2), with no significant differences observed between days. Despite a significant difference existing between testing day one and testing day two for performance of CMJ, one could conclude that a learning effect does not exist, as the values decrease between day one and testing day two. In addition, when considering the effect size presented for CMJ is trivial (Partial eta squared = 0.329), the significant differences noted between session one and session two could be questioned. The reasons for this difference could perhaps be explained by the CMJ strategy employed by the players. The depth that players moved to on testing day one and testing day two may have differed despite attempts made to standardise the protocol, yet this is not considered a concern as this study wanted to identify variation across testing days.

As reported in similar research assessing jump performances using the *OptoJump*, Glatthorn et al. (2011) considered *OptoJump* to be reliable for detecting changes in longitudinal assessments verifying the effectiveness of training programs, when assessing CMJ and SJ. Glatthorn et al. (2011) noted high ICC values (mean 0.985) and random errors averaged 2.81 cm (2.7%). Within this study, SDD was noted as 0.65 cm (1.7%) for CMJ and 1.08 cm (3.0%) for SJ. When trying to identify NMF using CMJ, jump height, assessed from flight time using the force plate, has been considered to be the most precise and reliable instrument. However, in many team-based scenarios a force plate is not readily available, therefore the *OptoJump* would be the next best alternative, with a difference of greater than 0.49 cm (1.3%) signifying a meaningful change within-session and a difference of greater than 0.65 cm (1.7%) signifying a meaningful change between session. Despite differences existing between session one and session two, the sensitivity identified for CMJ (0.65 cm; 1.7%) is a positive finding of this research and one that should be considered by practitioners.

4.5.3 Limitations of this study

The small sample size within this study could be considered a limitation, yet the implementation of effect size calculation alongside RMANOVA in accordance with recommendations by Buchheit (2016) to assess magnitude dispute this. The trivial effect size findings in this study therefore further supports the use of this small sample size utilising elite rugby union players. Another possible limitation of this study surrounds the self-selected jump protocol for all jumps by the players. Players were noted to adopt differing jump techniques, mainly whereby; depth of both SJ and CMJ on the downward phase varied and width of stance was individually selected which could have altered results. In addition, the technique adopted during the SLDJ-L and SLDJ-R differed mostly on the start of the jump where some players were noted to “drop off” the box and some were noted to “jump off” the box onto the landing surface below. It, however, could be argued that this variability in jump technique improved the ecological validity of this study, as not all players would move in the same manner possibly due to innate locomotion skills developed from an early age.

4.6 Practical Applications

Despite unilateral jumps being likely to identify NMF more easily, results from this research question their reliability. The large discrepancies in results for unilateral jumps, mainly associated with participant technique adopted, mean that bilateral jumps should be used for performance assessment instead of unilateral, with CMJ being the jump modality that would produce the most reliable measure of performance. A change of 0.65 cm (1.7%) can be considered meaningful when assessing elite rugby union players performing CMJ and therefore this value can be implemented to assess performance measures and readiness on a daily basis.

4.7 Implications of experimental chapter 4 for subsequent studies

The identification of CMJ as more reliable than SJ and SLDJ means that a need now exists to assess if CMJ assessment conducted on an *OptoJump* is as valid as that of the “gold standard” force plate. Assessment of *OptoJump* validity is of importance, as the applied “real world” setting within which future time-course of restoration of performance investigations are to be conducted is not suitable for regular force plate use. In addition, jump height needs to be compared against kinetic measures to warrant its use in following experimental chapters.

5 Countermovement Jump in Elite Rugby Players – A comparison between devices

5.1 Abstract

Methods of assessing power output via optical measuring systems have been questioned, despite force plates used in many environments due to their accurate measurement of jump height. Force plates are, moreover, expensive and impractical for use in many team sport settings. This study determined the validity of the *OptoJump*, which calculates jump height from flight time, by comparing CMJ height measured by the same method on a force plate. This study also compared CMJ performance, using an *OptoJump* measuring flight time, to that of a force plate using the take-off velocity measure, to examine jump height as an effective measure of neuromuscular performance, while also providing a “sense check” for *OptoJump* validity. Lastly, jump height measured on a force plate using velocity of centre of mass at take-off was compared to that of a force plate using the flight time measure, with the assessment of eccentric RFD also considered within this analysis. Results from this study indicate that a significant correlation exists between CMJ height measured on an *OptoJump* and CMJ height measured on a force plate also calculated via flight time ($\rho = 0.907$; $p < 0.05$; $r = 0.924$), therefore supporting *OptoJump* use. Weaker correlations were, however, noted between *OptoJump* CMJ height and CMJ height measured on a force plate via velocity at take-off ($\rho = 0.202$; $p > 0.05$; 0.449) and between CMJ height measured on a force plate via flight time and CMJ height measured on a force plate via velocity at take-off ($\rho = 0.210$; $p > 0.05$; 0.410), which could possibly be explained by subjects not standing still on the force plate prior to jump commencing, thereby affecting the determination of bodyweight. Additionally, results support the use of *OptoJump* jump height (CV < 10%) when compared against eccentric RFD, which when assessed on a force plate exhibit lower reliability between sessions (CV > 10%). Jump height from CMJ on an *OptoJump* is therefore recommended as a reliable measure of neuromuscular performance and provides support for the use of CMJ as a means for assessment within real world settings where use of force plates is unrealistic.

5.2 Introduction

Jump testing protocols have been scrutinised, with specific jump and power testing tools coming under criticism, mainly due to incorrect data analysis methods and/or the testing of subjects who are incapable of performing the jumps correctly. Numerous instruments measuring jump height and contact time (using different technologies and calculations) have provided varying results (Markovic et al., 2004). Force plates have been considered the “gold standard” for the measurement of jump tests and have been reported to provide excellent measurement accuracy for estimation of power via forward dynamics, calculated by the force applied to the jumping surface (Owen, Watkins, Kilduff, Bevan, & Bennett, 2014; Walsh et al., 2006). Jump instruments, such as optical measuring systems that solely assess flight time and do not determine jump height from the impulse momentum relationship, as used by Domire and Challis (2007), are open to question, as subjects can alter jump technique, such as a flexed foot on landing to increase flight time. By contrast, force plate assessment, which uses vertical velocity of the centre of mass at take-off, provides a more accurate measure of jump height, using a forward dynamics approach. The optimal method of determining take-off velocity during jumps is proposed by Owen et al. (2014) to involve analysis of the corresponding

vertical component of the ground reaction force (VGRF). The VGRF is calculated from the time before (30 ms) the start of the jump until take-off, with the impulse momentum relationship applied to determine velocity of the centre of mass. Its reliability was supported in prior research (variability $\leq \pm 1\%$) (Street, McMillan, Board, Rasmussen, & Heneghan, 2001). Owen et al. (2014) recommended the implementation of a 1000 Hz sampling frequency, with the mean ground reaction force measured for one second while stationary prior to jump, in order to enable valid measurement of bodyweight, which is integral to forward dynamics calculations.

The main disadvantages associated with force plates are that they are expensive to use and often impractical in field-testing scenarios (Casamichana et al., 2013). Methods of assessing neuromuscular function via kinetic methods, such as the force plate, have been criticised regarding data collection and analysis procedures, due to their influences on power output calculations (Cormie et al., 2007). Significant differences have been noted between jump height measured via change in centre of mass displacement and jump height calculated using flight time or take-off velocity (Aragon-Vargas, 2000). Much of the criticism regarding the use of kinetic measures concerns the difficulty in quantifying such measures and with the result that the frequency of their use is limited. Forward dynamics has been used to assess jump performance in previous research (French et al., 2004; Owen et al., 2014), with good reliability noted (Aragon-Vargas, 2000). Aragon-Vargas (2000) assessed four different methods of calculating vertical jump height, showing good reliability within-session for all ($r = 0.97$), with the change in centre of mass displacement measure used as the criterion against which to compare the other methods. The results demonstrated that flight time yields a valid and reliable measure of vertical jump performance, with the other three jump measures (two methods based of force plate vertical take-off velocity and one based on flight time) showing excellent validity ($r = 0.97$) compared to the change in centre of mass displacement measure.

CMJ use for assessing change in performance within rugby union is commonplace (Argus, Gill, Keogh, et al., 2012; Darrall-Jones, Jones, & Till, 2015; Gathercole, Sporer, & Stellingwerff, 2015; Roe et al., 2015), yet the analysis of CMJ has generally been limited to jump height assessment and only relates to the concentric phase of vertical jumps (Cormie, McBride, & McCaulley, 2009). Recent research (Gathercole, Sporer, & Stellingwerff, 2015; Kennedy & Drake, 2017a) has therefore looked at each of the phases of the jump and the way in which the subject moves throughout this triple flexion and triple extension movement. The three commonly reported phases of CMJ include the unweighting phase, the braking phase and the propulsive phase, yet these phases are often misunderstood when assessing force-time curves alone. The unweighting phase involves the onset of downward movement of the trunk to the peak negative velocity; while the braking phase involves the deceleration of the downward movement from peak negative velocity to when the movement becomes stationary. Lastly, the propulsive phase involves movement starting from the lowest position of the centre of mass to the instant of take-off when performing a CMJ.

Support for the reliability of *OptoJump* has previously been reported by Glatthorn et al. (2011), who noted very high ICCs for CMJ height derived from flight time on both an *OptoJump* and CMJ height measured on a force plate via flight time, despite systematic differences occurring between instruments (-1.06 cm; $p < 0.001$). Glatthorn et al. (2011) noted excellent test-retest reliability of the *OptoJump* CMJ height measurement (ICC 0.989; CV 2.2%), although the jump protocol implemented in this study and the subjects used were not considered elite and therefore comparisons should be made cautiously. Additional previous research (Cormack, Newton, McGuigan, & Doyle, 2008) has calculated the reliability of CMJ variables in elite

Australian rules football players, reporting high reliability within (1.1 – 1.7%) and between sessions (1.0 – 5.7%) for multiple kinetic measures. However, findings by Nibali, Tombleson, Brady, and Wagner (2015) noted average eccentric RFD not to be reliable (CV 21.3%), with concern therefore advised, as average eccentric RFD may not be sensitive to training induced changes. When assessing kinetic data, Nibali et al. (2015) also noted that vertical jumps tasks can be performed without the need for familiarisation, with average concentric force and concentric impulse being highly reliable (CV 2.7%), although jump height was noted as the only variable to display a % CV smaller than the SWC. When considering these findings by Nibali et al. (2015), the need for validity of this measure for testing both within and between sessions is needed.

Other research of interest regarding kinetic measures includes that by Marques et al. (2014), who assessed vertical jumps and reported jump height, RFD and peak force all to be highly reliable (jump height CV 7.0%, ICC 0.89; RFD CV 11.6%, ICC 0.91; peak force CV 6.1%, ICC 0.92). However, research showing relationships between eccentric RFD and CMJ performance are conflicting with McLellan et al. (2011d) assessing the RFD on vertical jump performance and noting poor retest reliability (CV 16.3%) within twenty three physically active men. McLellan et al. (2011d) did, on the other hand, note that significant correlations between maximum RFD and jump height could only explain 46% of the variance noted in jump height and that the other variance is likely to be due both to the inexperience of the subjects performing this explosive movement and the testing protocol implemented. Additionally, research by Ebben et al. (2007) noted no correlation between average RFD and CMJ ($r = 0.19$, $p = 0.22$) and therefore questioned the usefulness of RFD for assessing CMJ performance.

The aim of this study was to compare CMJ performance using different devices; one using jump height measured via flight time on an *OptoJump* and two methods of assessment from a force plate, using firstly velocity of centre of mass at take-off and secondly flight time. The results of this research will also determine test re-test reliability of a jump height measurement; thereby providing a “sense check” for future chapters within this thesis and informing on whether or not jump height alone can demonstrate sensitivity of neuromuscular performance when assessed via CMJ. Based upon prior findings (Glatthorn et al., 2011; Jensen, Furlong, Graham, & Harrison, 2011), it was hypothesised that jump height from CMJ on an *OptoJump* would be just as valid a measure of neuromuscular performance compared to jump height calculated on a force plate. Additionally, based upon prior findings (McLellan et al., 2011d; Moir et al., 2009; Nibali et al., 2015) it was also hypothesised that RFD for assessing jump performance is not as reliable a measure of assessing neuromuscular performance compared to jump height. This notion therefore supports the use of CMJ using the *OptoJump* as a means for assessment within real world settings, where the time consuming analysis associated with force plates means their use is often unrealistic.

5.3 Method

5.3.1 Participants

Seven elite rugby union players (age 21.0 ± 4.7 years, height 185.0 ± 8.6 cm, mass 89.0 ± 8.2 kg) from the same professional rugby club volunteered for the assessment of the CMJ height against kinetic measures (jump height, and mean eccentric RFD). Participants were all healthy and active individuals who had no current injury issues. All subjects provided written informed consent to participate and Salford University Research and Ethics Committee

approved the study. The sample sizes used within both research groups were considered satisfactory in accordance with guidelines provided by Hopkins (2000).

5.3.2 Procedure

The assessment of two CMJ trials across three testing days was conducted, with no greater than seven days between each assessment. The CMJ protocol was standardised throughout the three testing days, with appropriate warm up given prior to testing and adequate rest administered between each trial. In accordance with previous research (Cunningham et al., 2013; McLellan & Lovell, 2012; McLellan et al., 2011b; West et al., 2014) that used kinetic measures (RFD) to assess neuromuscular function pre and post rugby union match play, this research used RFD to compare against CMJ performance. Jump Height (JH) measured in cm, and mean eccentric Rate of Force Development (RFD) measured in ($N \cdot s^{-1}$), provided more detail about CMJ performance and assessed the reliability of CMJ values when measured via *OptoJump*. A custom *Microsoft Excel* data collection sheet was used within this research to compare the validity of jump height between instruments and to calculate performances from force-time data against kinetic measures (JH and mean eccentric RFD), with the statistical analysis performed in SPSS.

Support for the use of using a 0% load for assessing jump performance in order to maximise power output was noted by Cormie, McBride, and McCaulley (2008), with McBride et al. (2002) also noting that acceleration of the system mass during a squat jump decreases as the external load is increased. This methodological rationale is also more practically relevant for use within elite settings, as it is often not viable to implement loaded jumps in competition and training settings. Players wore appropriate footwear for each jump and were given the same verbal instructions pre each attempt. Despite the testing being conducted post-match, the influence of games was considered to be unlikely to have an influence upon results, as the time-points of assessment were consistent throughout this study and the training and match protocol prior to testing commencing on each occasion was standardised. In addition, as the players tested within this study were accustomed to games and as this testing was conducted during the normal competitive phase of the players' season, possible effects of match fatigue were unlikely to have an adverse impact upon results.

5.3.2.1 Countermovement Jump (CMJ) technique

The CMJ was performed from a standing position with the whole plantar part of the foot touching the jumping surface with the hands resting on the hips. A rapid counter movement was conducted by the participant until the knee angle reached approximately 90°, then immediately, the participant jumped as high as they could, with their legs remaining straight upon flight, therefore preventing any tucked legs which would lead to inaccurate measurement of jump height derived from flight time. Upon landing the participants made contact with the testing surface with legs extended, only flexing the knees enough to absorb the impact once contact had been made with the floor. Prior to each jump the participant was encouraged to jump as high as possible. Post-jump, participants received verbal feedback about their performance.

5.3.2.2 Instruments

5.3.2.2.1 Force plate

The force plate used in this study was a *400s Performance Force Plate* (Innervations, Adelaide, Australia) operated by software (*Ballistic Measurement System, Fitness Technology*). The force

plate was set to record for five seconds, sampling at 600 Hz, initiated using an external trigger. This sampling frequency was well within the guidelines presented by Hori et al. (2009), who recommended that practitioners consider sampling as low as 200 Hz for CMJ assessment. The force plate was zeroed before testing commenced, so that the weight of the participant would not influence the measurement. The threshold for determining take-off and touchdown was set at 5 N for all participants, in line with other recent research (Castagna et al., 2013).

5.3.2.2.2 OptoJump

The *OptoJump* (Microgate, Bolzano, Italy) was used to assess flight time and to compare against the criterion method of take-off velocity on the force plate, which had previously been shown to have excellent reliability (Glatthorn et al., 2011). Similarly to this study, Twist and Sykes (2011) used an *OptoJump* in their study of exercise induced muscle damage from simulated rugby league match play. The *OptoJump* (previously reported in more detail within chapter 4.3.3.1) was placed on top of the force plate on the gym floor, with players standing between the *OptoJump* bars when jumping.

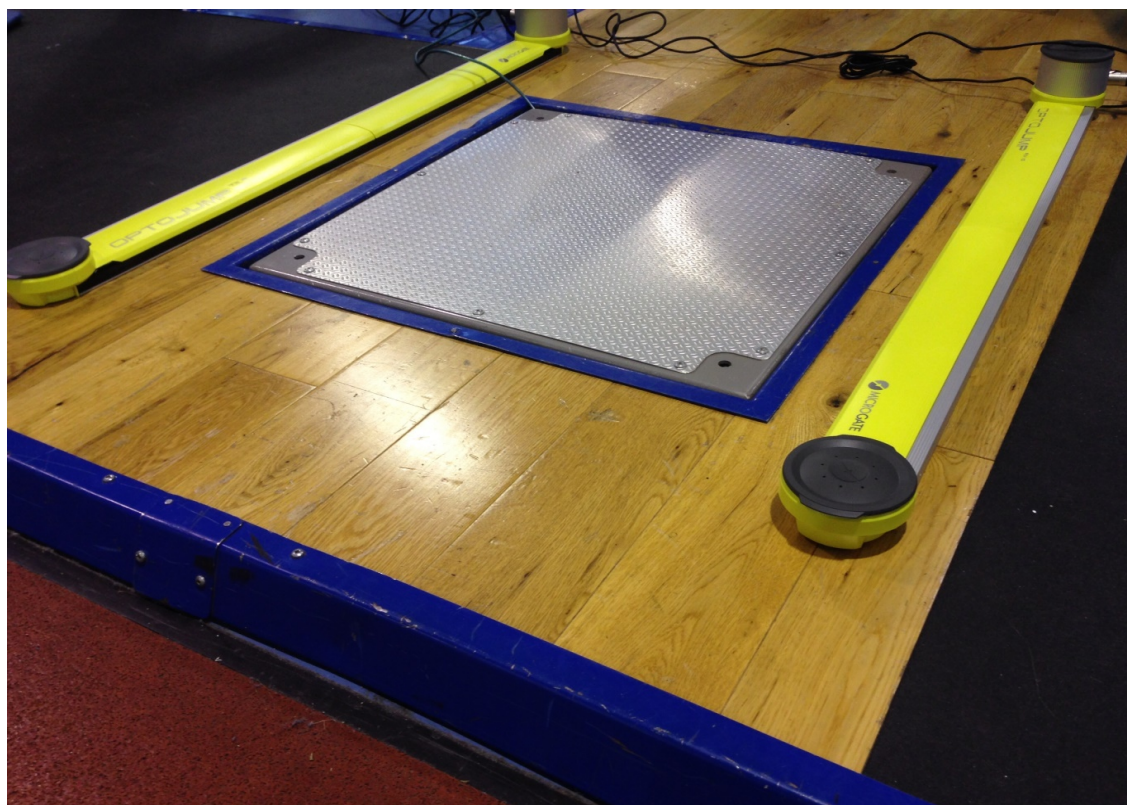


Figure 5.1: An illustration of the test set-up, showing the *OptoJump* sitting alongside the force plate

5.3.2.3 Data analysis

5.3.2.3.1 Jump Height and Flight Time

Flight time was used to calculate OptoJump jump height, with both flight and take-off velocity used to calculate jump height from force plate force-time data. Jump height was calculated via flight time, using the following equation utilised by McMahon et al. (2015), adapted from that proposed by Bosco et al. (1983).

$$\text{Jump Height} = (9.81 \text{ m.s}^{-2} \times \text{flight time}^2) / 8$$

5.3.2.3.2 Force-time analysis

Force-time analysis uses the impulse-momentum relationship to determine velocity, which calculates power through the forward dynamics approach (Cormie et al., 2007). Kinetic variables were assessed for both the eccentric and concentric phases of the CMJ. Eccentric RFD concerns the average force exerted during the eccentric phase of the CMJ and is measured in $N.s^{-1}$, with the ability to handle the maximal eccentric force in the minimal time possible being a typical indicator of explosive strength. RFD relates to short duration components of the SSC and are characterised by time-displacement (100 to 250 ms) of the ankle, knee and hip joints during CMJ. The eccentric phase consists of the point in the downward movement where the force being exerted into the force plate exceeds body weight, until the point of zero velocity at the lowest point of the countermovement. In recent times, the use of RFD has been employed as a more specific predictor of explosive strength, in contrast to the term “power” that is used to indicate maximal exercise performance. Similarly, as reported by Gathercole, Sporer, Stellingwerff, et al. (2015a) and based upon the research by Owen et al. (2014), jump start threshold in this study was set at five times the standard deviation of the noise, in order to calculate the start of the movement and to improve accurate data collection.

Previous research has utilised the flight time calculation via the height of rise of centre of mass (French et al., 2004; McBride et al., 1999, 2002). The vertical take-off velocity of the centre of mass is calculated, whereby acceleration (a) is determined by dividing vertical ground reaction forces (F) by the mass of the system (SM) at each time point. As acceleration and velocity are two different measurements, acceleration is multiplied by time to provide velocity:

$$a = F/SM$$

Jump height (JH) from velocity of centre of mass was calculated via the following equation:

$$JH = (v^2)/(2 \times 9.81)$$

$$v = \text{displacement/time}$$

5.3.3 Statistical Analyses

All statistical analysis was conducted on SPSS for windows, with an *a priori* alpha level set at $p < 0.05$. Reliability was determined using RMANOVA with Bonferroni post-hoc analysis, or non-parametric equivalent. Effect sizes (ES) were also determined using the Cohen's d method and interpreted based on the criteria suggested by Rhea (2004); trivial = < 0.25 , small = $0.25 - 0.5$, moderate = $0.50 - 1.0$ and large > 1.0 . Post-hoc statistical power was calculated using G Power 3.1 (Faul et al., 2009), for a large effect size of 0.5, a total $n = 7$ was sufficient to deliver an actual power of 0.69. In addition, partial eta squared was assessed to see if there were any meaningful differences between testing days, as reported and recommended by Cohen (1988). Within-session reliability was tested via intraclass correlation coefficients (ICC) (Model 3, 1). The reliability was considered acceptable if the $ICC \geq 0.8$ (Cortina, 1993). SEM and smallest detectable differences (SDD) were calculated in order to provide information for on whether or not a change in an individual's performance was significant, with SEM calculated using the formula: $SD(\text{pooled}) * (\sqrt{1 - ICC})$ and SDD calculated from the formula: $((1.96 * (\sqrt{2})) * SEM)$. In line with previous research (Cormack, Newton, McGuigan, & Doyle, 2008; Marques et al., 2014; McMahon et al., 2016), assessing jump performance measures in both team and individual sports, a measure must demonstrate a $CV < 10\%$ to be considered reliable, with practitioners therefore needing to assess, if this change is of practical significance.

5.4 Results

5.4.1 Jump height measures from *OptoJump* and force plate

Shapiro Wilks tests of normality revealed that *OptoJump* jump height; force plate jump height (flight time and take off velocity) and eccentric RFD were not normally distributed ($p < 0.05$). Reliability statistics demonstrated that *OptoJump* jump height displayed a higher CV within-session than eccentric RFD. Within-session CMJ height assessed on a force plate, was, however, lower than that presented for *OptoJump* jump height (Table 5.1).

Between-session reliability was considered to be acceptable for *OptoJump* jump height, force plate jump height from flight time eccentric and RFD measures of CMJ ($ICC > 0.8$), although not for jump height from velocity at take-off on a force plate. *OptoJump* jump height, force plate velocity at take-off and force plate flight time illustrated lower SDD than eccentric RFD (Table 5.2). A strong positive Spearman's correlation was noted when comparing *OptoJump* jump height and force plate jump height with flight time ($\rho = 0.907$; $p < 0.05$; $r = 0.924$) (Figure 5.2), yet poor correlations were noted between force plate velocity at take-off and force plate flight time ($\rho = 0.210$; $p > 0.05$; $r = 0.449$) (Figure 5.3) and between jump height from velocity at take-off on a force plate and jump height derived from flight time on an *OptoJump* ($\rho = 0.202$; $p > 0.05$; $r = 0.410$) (Figure 5.4).

Table 5.1: Descriptive (mean \pm standard deviations) and reliability statistics, within testing days for CMJ height and RFD ($N.s^{-1}$)

CMJ	Day 1 average	Day 1 %CV	Day 2 average	Day 2 %CV	Day 3 average	Day 3 %CV	All sessions average	Average %CV
CMJ Height <i>OptoJump</i> (cm)	39.1 \pm 0.03	8.31%	37.6 \pm 0.02	7.23%	37.8 \pm 0.04	10.70%	38.2 \pm 0.03	8.74%
CMJ Height Force Plate (Flight time) (cm)	40.6 \pm 0.01	1.69%	39.7 \pm 0.01	1.82%	39.8 \pm 0.01	2.92%	40.0 \pm 0.01	2.14%
CMJ Height Force Plate (Velocity at Take-off) (cm)	39.6 \pm 0.05	1.50%	36.8 \pm 0.08	2.21%	35.6 \pm 0.02	0.56%	37.3 \pm 0.05	1.42%
CMJ Eccentric RFD ($N.s^{-1}$)	5242 \pm 443	8.9%	4841 \pm 466	10.50%	5286 \pm 330	6.56%	5123 \pm 413	8.67%

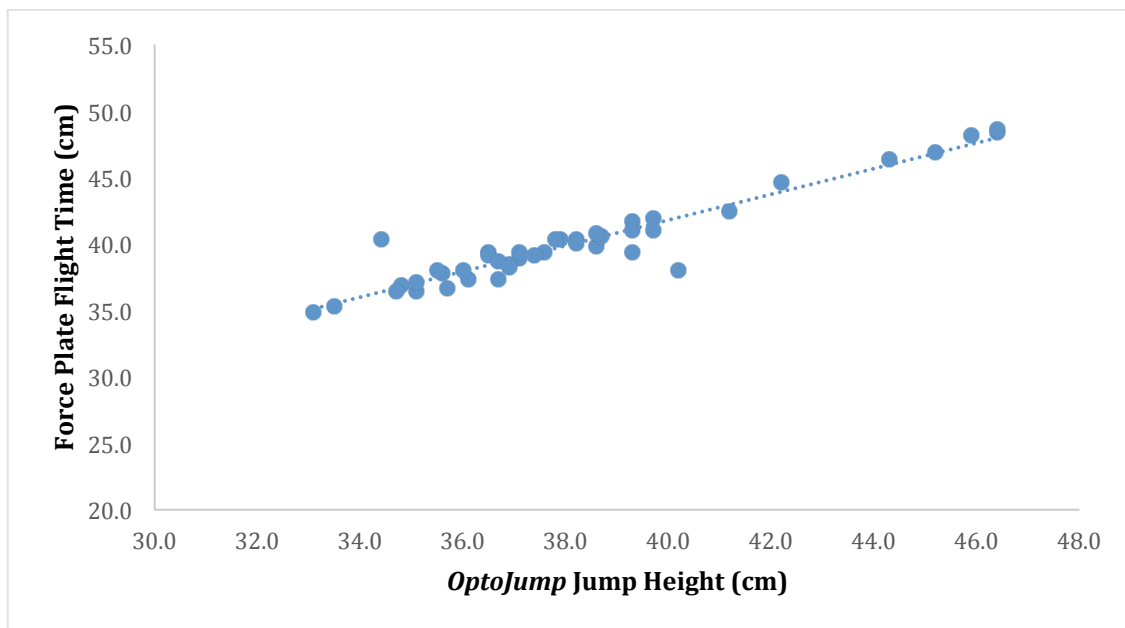


Figure 5.2: Relationship between *OptoJump* jump height (from flight time) and force plate flight time during the same jump, using pooled data

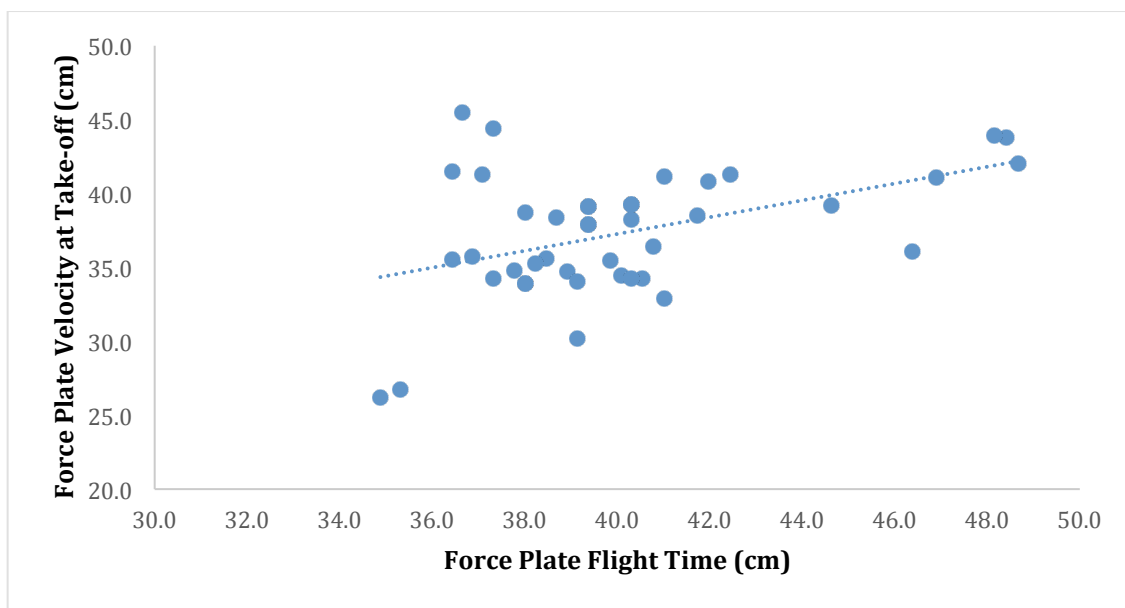


Figure 5.3: Relationship between jump height from flight time on a force plate and jump height derived from velocity at take-off on a force plate, using pooled data

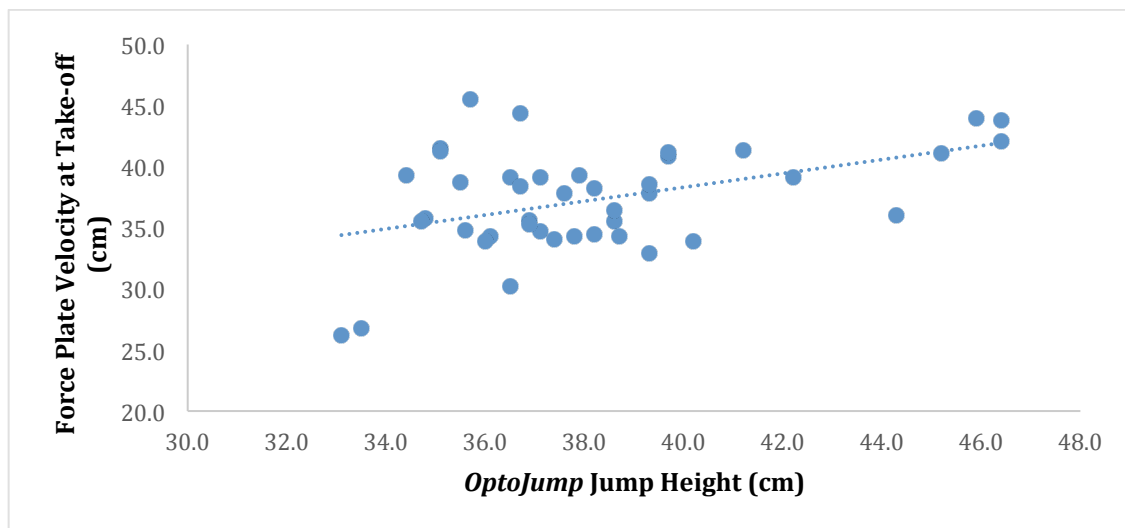


Figure 5.4: Relationship between jump height from velocity at take-off on a force plate and jump height derived from flight time on an *OptoJump*, using pooled data

Table 5.2: Descriptive (mean \pm standard deviations) and reliability statistics, between testing days for CMJ height (cm) and RFD ($N.s^{-1}$)

Jump	Day 1 (cm)	Day 2 (cm)	Day 3 (cm)	ICC r	Partial eta squared	SEM (m)	SDD (m)
OptoJump CMJ Height (cm)	39.1 \pm 0.03	37.6 \pm 0.02	37.8 \pm 0.04	0.895	0.192	0.01	0.03 (7.9%)
Force Plate CMJ Height (Flight time) (cm)	40.6 \pm 0.01	39.7 \pm 0.01	39.8 \pm 0.01	0.923	0.103	0.00	0.02 (6.7%)
CMJ Height Force Plate (Velocity at Take-off) (cm)	39.6 \pm 0.03	36.8 \pm 0.02	35.6 \pm 0.04	0.728	0.528	0.00	0.02 (6.2%)
CMJ Eccentric RFD Force Plate ($N.s^{-1}$)	5242 \pm 1264	4841 \pm 1721	5286 \pm 1741	0.921	0.111	450.0	1247.5 (24.3%)

5.5 Discussion

The results presented indicate that a significant correlation exists between *OptoJump* CMJ height measured via flight time and CMJ height measured via flight time on a force plate. Results from this study would indicate that *OptoJump* jump height is a jump performance metric that can be used in elite sport settings where accessibility to force plates within different training environments are difficult, therefore supporting *OptoJump* use.

5.5.1 Jump height measures from *OptoJump* in comparison to force plate

The R^2 value of $p = 0.907$ presented in figure 5.2 above illustrates that a linear relationship exists between *OptoJump* jump height and force plate jump height, with the correlation coefficient of $r = 0.924$ further supporting this notion. This study and that of previous research (Cormack, Newton, McGuigan, & Doyle, 2008) note that jump height is the most reliable of the variables measured, therefore disagreeing with the claim by Gathercole, Sporer, and Stellingwerff (2015) that jump height reflects a gross performance measure. Gathercole, Sporer, and Stellingwerff (2015) argued that despite players being asked to jump as high as possible, it seems that the outcome and subsequent values presented are more likely to manifest themselves in measures directly related to the force plate rather than the resultant jump height performed, with future assessment of jump performance recommended to include

kinetic measures instead. The results of this study do not dispute this notion of altered jump mechanics, but do show that jump height is a simple and reliable measure to be used when kinetic measurement tools are perhaps not available.

It is also important for practitioners to note that the mean jump height values reported within previous research (Jensen et al., 2011; Marques et al., 2014) were lower (26 cm) than those noted within this study. This finding, along with the lower CV values identified, could perhaps be explained by the lower athletic level of the subjects involved. Alongside the incorporation of sub-elite level rugby players in the research by Jensen et al. (2011), it is of note that the use of arm swing was allowed during jump completion, whereas no arm swing was allowed within the testing protocol implemented within this experimental study, meaning that caution regarding comparison would be advised. Previous research (Klavara, 2000; McLellan et al., 2011d) has shown that the use of arm swing will result in an increase in take-off velocity when compared to using no arm swing. When combining knowledge of the use of arm swing with the findings in research by McLellan et al. (2011d), who used a *Vertec* to assess jump height, any resultant comparison of jump height values between studies should be questioned. More crucially, as the *Vertec* has been shown to overestimate jump height in contrast to the calculation from a force plate, comparison between some studies is better discounted altogether (Ferreira, Schilling, Weiss, Fry, & Chiu, 2010). Differences in ability of the participants and the tools used to assess jump performance could, perhaps, explain the differences seen in the CV's reported. The results from this study would, however, support the views of Jensen et al. (2011) for using *OptoJump*, when a force plate is not available. Although any comparison between jump height values would be discouraged, where participants and methodologies differ.

In a study assessing the validity of using a wearable accelerometric system (*MyoTest*) for assessing vertical jump height (Casartelli et al., 2010), it was noted that jump height measured via flight time on a *MyoTest* overestimated jump height compared to *OptoJump* ($p < 0.001$), with a systematic bias of 7 cm noted, despite a high reliability shown (> 0.98). This systematic error shown for jump height assessed via flight time could partly explain the differences noted in jump height values reported between instruments in this experimental study, while perhaps providing further rationale for the lower reliability noted within-session for *OptoJump* compared to RFD. Within the research by Casartelli et al. (2010) it is, however, important to note that two calculation methods (flight time and vertical take-off velocity) were used to estimate jump height measured on the *MyoTest*. The peak velocity calculated during the jumping movement, therefore should be questioned, as it does not relate specifically to take-off velocity. Additionally, peak negative velocity is actually a measure of impact which can consequently lead to overestimation within calculations. The results of this study illustrate a 2 cm difference in jump height calculated from force plate compared to those taken from *OptoJump*. However, when considering that the force plate measurements taken within this study also incorporated jump height from flight time and jump height from velocity of centre of mass at take-off, relevant comparison can therefore be made with the research of Casartelli et al. (2010).

The comparison of the results of this study with prior research is ill advised, as the testing protocol implemented within different studies is likely to vary. The complexity of any testing protocol associated with force plates, means that discrepancies in data collection are probable. One area of concern is the need to make subjects remain still on a force plate prior to jumping. Practitioners cannot assume that subjects are made to remain still on a force plate prior to jumping, as was implemented in prior research (Owen et al., 2014; Street et al., 2001) and this

notion can perhaps explain much of the erroneous data produced. Protocol in this experimental study did not enforce a period of standing still and it could therefore be assumed that this impacted negatively upon the velocity measurements produced. This testing protocol and resultant data produced could, however, be considered a “real world” consequence of force plate testing, and where the alternative expectation of players being enforced to stand still prior to jump movement is perhaps unrealistic. As a consequence, as observed in this study, many practitioners do not implement a standing still element prior to jump testing. Additionally, the complexity of obtaining accurate force-time data could perhaps explain why many practitioners who use a force plate only report jump height from flight time calculations instead of via forward dynamics. When considering that the vast amount of research in rugby has used vertical jump assessment (Darrall-Jones, Jones, & Till, 2015; McMahon et al., 2016; Till et al., 2015; Till et al., 2014; Twist & Highton, 2013; Twist et al., 2012), yet they report jump height instead of kinetic measures, it could be concluded that jump height alone captures what is needed by practitioners in applied settings. It could also be argued that many practitioners do not know how to determine forward dynamics, as its calculation is complicated, meaning that future research is likely to steer away from the implementation of force-time data, thus further adding to the confusion surrounding this performance testing measure.

5.5.2 Reliability of *OptoJump* and force plate

The results of this study demonstrate that jump height, measured via flight time collected during a single CMJ on both a force plate and an *OptoJump*, exhibits high reliability (CV < 10%; SDD < 10%). The average coefficient of variation presented for *OptoJump* jump height measured via flight time (CV 7.9%) is larger than the jump height measured via flight time on a force plate (CV 6.7%), yet both measures of jump performance exhibited high reliability within and between sessions (Table 5.1 and 5.2). It is, however, important for practitioners to note that the consideration of the between-sessions values is of more importance than the within-session, as the within-session values are not as important for assessing changes in fatigue required from this study, while the between-sessions values are likely to be more sensitive to this measure. Research, of interest for practitioners and that specifically relates to this experimental study, is offered by Jensen et al. (2011). When assessing reliability of jump measures in rugby union players, Jensen et al. (2011) presented high reliability (ICC 0.966; CV 5.1%) for *OptoJump* using the flight time calculation reported earlier (Chapter 5.3.2.3). Therefore comparisons between these results are warranted considering that similar methodologies used. The results collected within this experimental study illustrate that the reliability of *OptoJump* CMJ height is similar to that reported by Glatthorn et al. (2011), who noted very high ICCs (0.995 – 0.999) for both *OptoJump* CMJ height and CMJ height measured on a force plate. When considering that jump height measured on *OptoJump* is not measured by displacement and instead calculated by mathematical assumption, the varying reliability measures presented are perhaps of no surprise, with this finding supported by the systematic differences identified by Glatthorn et al. (2011) between *OptoJump* CMJ height and CMJ height measured on a force plate (-1.06 cm; $p < 0.001$).

In a meta analytical review of the reliability of power measurements in physical performance tests (Hopkins et al., 2012), it was noted that the lowest CV expected for the assessment of jump height was likely to be 2.0%, with Cormack, Newton, McGuigan, and Doyle (2008) reporting the reliability of jump height assessment taken from a single CMJ demonstrating in elite Australian rules players (CV < 5%). More recent research, specifically relating to rugby (Roe et al., 2015), showed acceptable reliability (CV 2.14%) for CMJ peak force, yet did not

report jump height reliability measures. Roe et al. (2015) did, however, report that such reliability testing should be both population and sport specific, which may explain the differing values, reported between studies. Previous research (Cormack, Newton, McGuigan, & Doyle, 2008; Taylor et al., 2010) assessing jump performance has adopted arbitrary threshold values of 10% CV as showing “good reliability”. Within this experimental study, both measures of jump height (*OptoJump* and force plate) therefore exhibit acceptable reliability between sessions (CV < 10%), as similarly classified within other jump performance research (Cormack, Newton, & McGuigan, 2008; Cormack, Newton, McGuigan, & Doyle, 2008; Taylor et al., 2010). Despite Aragon-Vargas (2000) noting excellent reliability (CV 13.4% to 18.3%) for vertical jump on a force plate, this study could argue that these values do not represent excellent reliability as, the values reported within Table 5.1 are lower, despite similar methods of assessment being used.

From the results assessing reliability between sessions, it is clear that jump height measured on the *OptoJump* offers less reliability (CV 7.9%), when compared against the force plate jump height. The between-session values noted for *OptoJump* CMJ height appear less reliable (ICC 0.775 – 0.895), than those of Glatthorn et al. (2011) (ICC 0.998). However, as the jump protocols implemented within the two studies differ, careful consideration is warranted prior to any comparisons being made. Not only, did the set-up of the *OptoJump* on the force plate differ between the studies, but also the force plate used and the sampling frequency set. This study would therefore support the views of Glatthorn et al. (2011), who noted that the discrepancy noted between *OptoJump* CMJ height and CMJ height measured on a force plate may be most likely explained by test set-up. The misalignment of the photoelectrical cells associated with the *OptoJump* could have explained some of the differences seen, alongside the notion that a subject’s foot may have broken the electrical cell but not yet landed on the force plate. In addition, it must be considered by practitioners that any potential difference in sensitivity of electrical cells (*OptoJump*), in comparison to that of vertical reaction forces (force plate), may also account for the differences noted.

Previous work, utilising a timing mat, has shown displacement of the centre of gravity in CMJ performed on a timing mat to be a reliable measure with CV of 6.3% (Arteaga, Dorado, Chavarren, & Calbet, 2000). Similarly, Markovic et al. (2004) also used a contact mat to determine CMJ reliability and reported an ICC of $r = 0.98$ and TE values of 2.8%. The research by Glatthorn et al. (2011) is perhaps the most useful for comparison to this experimental study, as the *OptoJump* was also used in determining reliability. Additional research of note for practitioners is that by Casartelli et al. (2010), which illustrated high reliability (ICC 0.92-0.96) for *MyoTest* (flight time), but poor reliability (ICC 0.56-0.89) for *MyoTest* (vertical take-off), therefore demonstrating the unsuitability of using flight time measurements and the importance of comparing similar calculations when assessing kinetic data.

Lastly, support for the reliability of CMJ height was noted by Cormack, Newton, McGuigan, and Doyle (2008) (CV 2.4%; ICC 0.93) when assessing elite Australian rules football players. Although the average CMJ height values reported by Cormack, Newton, McGuigan, and Doyle (2008) are higher (48.8 cm) than those reported within this research and the reliability reported is lower, (CV 5.2%), comparisons can still be made. The differences in reliability values between these studies could be explained by the methodology. Firstly, the study by Cormack, Newton, McGuigan, and Doyle (2008) involved athletes from Australian rules football and therefore their physical performance abilities of a CMJ are likely to differ. Secondly, it is also important to note that a larger sample size was incorporated within this study compared

to that of Cormack, Newton, McGuigan, and Doyle (2008). This, along with the sampling frequencies used also differing between protocols; perhaps explain the differences reported in reliability.

5.5.3 Jump height in comparison to RFD

Data in research settings that show a relationship between RFD and CMJ height is limited, although findings from this experimental study show that eccentric RFD measured on the force plate presents similar reliability values within-session (CV 8.6%) to that of jump height measured on the *OptoJump* (8.8%). Both within and between-session, jump height measured on a force plate illustrated the most reliable measure of CMJ assessment, therefore supporting its notion as the “gold standard” tool of measurement. The finding from this experimental chapter, reporting that jump height assessed via *OptoJump* illustrates lower reliability values (CV 8.8%) compared to RFD (CV 8.6%) within-session, is surprising. Kinetic measures are normally a more informative measure than jump height, but the contrasting findings from this study are perhaps due to the lack of a proper pre-jump “silent period” implemented. One cannot therefore dismiss the use of kinetic measures for jump performance assessment in future practice, but can include prior knowledge of aforementioned RFD inaccuracies when making judgements.

Despite the ability to develop force rapidly being a prerequisite for explosive strength, a scarcity of knowledge regarding RFD correlations to vertical jump exist. The availability of reliability statistics for eccentric RFD is limited, with Moir et al. (2009) reporting lower RFD values (CV 17-21%) than seen within this study, yet it must be noted that the values presented by Moir et al. (2009) are from non-elite men and women and therefore cannot be compared directly with the eccentric RFD values presented within this study (ICC 0.921, CV 24.3%). McLellan et al. (2011d) assessed RFD on vertical jump performance using a force plate, noting poor re-test reliability (CV 16.3%) within twenty-three physically active men. In relation to the results from this study, eccentric RFD also displayed low reliability. However, an important point for consideration when comparing the results from this study with the research of McLellan et al. (2011d) is that this study used a differing sampling frequency (600 Hz) to that of McLellan et al. (2011d) (1000 Hz). Additional findings by Nibali et al. (2015) noted eccentric RFD not to be reliable (CV 21.3%), with caution advised, as eccentric RFD may be sensitive to training induced changes. It is also important to note that Nibali et al. (2015) did observe that eccentric RFD was sensitive to fatigue, therefore supporting its use within fatigue assessment using jumping movements, as is proposed in later chapters of this study. As was recommended by Nibali et al. (2015) further investigation is warranted regarding the sensitivity of eccentric RFD to fatigue.

The results of research by Marques et al. (2014), assessing the reliability of time-force variables using a linear power transducer, are also of interest to this experimental study. Similar to this study, Marques et al. (2014) concluded that using jump height calculated during a CMJ constitutes a valid lower-body measure of performance. Marques et al. (2014) also assessed vertical jumps and reported jump height, RFD and peak force all to be highly reliable (jump height CV 7.0%, ICC 0.89; RFD CV 11.6%, ICC 0.91; peak force CV 6.1%, ICC 0.92). Within the research by Marques et al. (2014), RFD was demonstrated to have the largest correlation with jump height, with greater RFD being associated with greater jump height and RFD reported as likely to explain 69% of the variance in jump height reported. The use of a linear power transducer was noted as reliable by Marques et al. (2014) for assessing force-time data during CMJ and was recommended for use when the more expensive option of a force plate was not

available. Similarly to as noted within this study, Marques et al. (2014) concluded that using CMJ jump height constitutes a valid lower-body measure of performance. Within the research by Marques et al. (2014) RFD demonstrated the largest correlations with jump height, with greater RFD being associated with greater jump height and RFD likely to explain 69% of the variance in jump height reported. The research by McLellan et al. (2011d) also noted a significant relationship existed between vertical jump displacement (VJD) and PRFD for the CMJ ($r = 0.68$; $p = 0.001$), yet the results from this study would contradict these views, as, despite eccentric RFD within this study showing high ICC values, no correlation existed between *OptoJump* jump height and RFD, while the SDD reported, illustrates the variability associated with this kinetic measure.

Perhaps most importantly for future consideration within the assessment of RFD values, is the understanding of how this kinetic measure is calculated. Prior research such as McLellan et al. (2011d) reports poor reliability for RFD, but does not determine from where this measure was taken. This experimental chapter assessed eccentric RFD, yet other studies such as McLellan et al. (2011d) could have taken a concentric measure of RFD, or a combination of both eccentric and concentric RFD, resulting in two peaks on the force trace. This notion of poor classification and understanding of RFD assessment would therefore further support the use of *OptoJump* jump height. Further support for the reliability of jump height assessed via *OptoJump* is illustrated in this experimental study, where *OptoJump* (CV 7.9%) demonstrated better reliability values compared to RFD (CV 24.3%), when assessing CV values alone. Figures 5.3 and 5.4 showed that poor variability in assessment occurred within kinetic measures, as was illustrated by the correlation values presented. The weak correlations existing between, firstly, jump height measured on an *OptoJump* and jump height collected on a force plate from velocity at take-off and secondly jump height collected on a force plate from velocity at take-off and jump height collected on a force plate via flight time, are most likely to be explained by the lack of a proper pre-jump silent period.

5.5.4 Limitations of this study

When considering that some participants may have carried over a level of fatigue or muscle soreness into these testing days, the resultant influence this may have had upon the CMJ performance needs to be noted. Despite the testing being conducted during the competitive phase of a playing season and testing standardised post each game, the influence of training and or lifestyle choices may have influenced the CMJ performance. These limitations are considered to be “real world” factors in testing elite players, where days between games vary, training load is often high and the notion of practitioners being able to influence training schedules based upon the need for ensuring reliability of test results is unlikely. Additionally, a further potential limitation of this research surrounds the relatively small sample size ($n=7$) used within this experimental study. An increased sample size would have added greater depth and breadth to the knowledge base of a CMJ height on an *OptoJump* in comparison to that taken from a force plate.

Another potential limitation of this study is the protocol implemented. It could be argued additional analysis of all phases and related characteristics of a CMJ would benefit practitioners when assessing changes in performance. Phases of a CMJ such the un-weighting phase and the braking phase would provide more information on the neuromuscular strategy of the jump. However, as previously discussed it is important to note that a protocol of kinetic measurement using a force plate is unrealistic for this setting and is instead better for research purposes. Assessment using force plate would not be time-efficient for a squad of up to 50 rugby players,

where there are likely to be time pressures from coaches to complete training sessions and post-match debriefs, prior to the next game commencing. Lastly, within this study the incorporation of the *OptoJump* 3mm above the force plate was not considered a concern, as this analysis was conducted with the aim of assessing the reliability of the same instrument and was standardised throughout testing. However, the results from the study by Healy, Kenny, and Harrison (2016), showing an underestimation in flight time when assessing drop jumps (RSI), are worth consideration. Healy et al. (2016) noted that this underestimation could perhaps be explained by differences in the calculation of FT:CT, with regression equations therefore advised for the future, in order to ensure valid interpretation of study data.

5.6 Practical Applications

The aim of this study was to compare jump height from *OptoJump* and force plate, investigating the notion that jump height alone “overlooks” fatigue related neuromuscular changes and that the implementation of kinetic CMJ performance evaluation would add more relevant information. Despite recent research by Gathercole, Sporer, Stellingwerff, et al. (2015a) assessing fatigue sensitivity of CMJ and reporting that jump height should be considered representative of the “outcome” of jump performance and not reflect the neuromuscular strategy of the jump, the results from this study somewhat contradict this notion. Gathercole, Sporer, Stellingwerff, et al. (2015a) claim that jump height measures alone misinterpret the phases associated with vertical jumping and therefore ignore important data. Results from this study, would not dispute their view, yet the finding that jump height taken from flight time measured on a force plate, presented only slightly better reliability than jump height measures on an *OptoJump* are of importance. Consideration of the notions of Gathercole, Sporer, and Stellingwerff (2015) regarding the phases associated with vertical jumping is, however, worthwhile. When considering that *OptoJump* measures are more easily obtained and incur fewer cost implications, the justification for the inclusion of kinetic measures can be questioned. The results of this study support the use of *OptoJump* jump height to assess performance change as a result of the influence of rugby training and matches. Lastly, it is perhaps advisable for practitioners to note that Cormie et al. (2009) recommended the examination of changes to the power, force velocity and/or displacement time-curves as being a useful tool for longitudinal assessment. In comparison to using analysis of performance variables alone these should therefore be considered for inclusion in future investigations.

5.7 Implications of experimental chapter 5 for subsequent studies

The confirmation of the use of CMJ height measured on an *OptoJump* leads the next investigation of this thesis towards the assessment of CMJ height between rugby matches. As was illustrated in the review of literature, fatigue is present in the days post-match, yet the reliability of CMJ height testing between matches needs to be examined. Improved clarity upon the reliability of CMJ height testing in the days between matches will better enable more accurate assessment of time-course of restoration in future experimental chapters.

6 Between-Session Reliability of a Countermovement Jump in Elite Rugby Players Pre Game

6.1 Abstract

Jump tests are considered to be excellent indicators of neuromuscular function for team sport athletes, due to the stretch-reflex actions seen in jumping. In many elite team sport settings, jump testing is used to assess small but important changes in performance, although the reliability of CMJ between games is yet to be identified in elite level rugby union. Decrement in jump performance post-match rugby match has been reported to exhibit decreased values for up to 24 hours, with CMJ previously reported to measure fatigue accurately. Daily application of multiple jump modalities is unrealistic, with many practitioners using CMJ assessment in preference to other jumps, due to its relevance and familiarity within elite team sport settings. A specific testing protocol that measures CMJ performance between games and enables instant interpretation of meaningful change is, however, required. This study aimed to assess the reproducibility of one CMJ between sessions, using an *OptoJump*, which measures flight time and permits the calculation of jump height. Results from this study indicate that between sessions a single CMJ shows high reliability (CMJ ICC = 0.986, SDD 2.4%), with no significant differences ($p > 0.05$) in jump height observed between days. Performance of a single CMJ (measuring jump height) on an *OptoJump* is therefore considered to be a reliable measure for assessing post-match levels of readiness when a force plate is not readily available, with advice for practitioners that changes of $> 2.4\%$ should be considered meaningful.

6.2 Introduction

Jump tests have commonly been used for assessing changes in performance, as jumps are a convenient exercise to implement into a high performance sport settings and providing great ecological validity. Jump testing has, however, come under scrutiny because of the technique that many subjects use and the inconsistent testing protocol administered (Markovic et al., 2004). An individual's ability to generate force quickly is a key performance measure for athletes competing in many team sports; hence jump tests have been commonly used. Testing irregularities such as the subject's ability to swing their arms for greater height mean that recent jump testing has focused solely on the SJ and CMJ. CMJ involves the use of the stretch shortening cycle (SSC), whereby subjects perform a downward movement from an erect standing position until they feel comfortable and then jump for height in an upward motion. The assessment of the mechanics involved within this movement, provide valuable detail for future training prescription (Argus, Gill, Keogh, et al., 2012; Argus et al., 2009; Baker, 2001c).

In addition to using jump tests that measure power, velocity, force, contact time and rate of force development; recent research has focused on utilising vertical jumps to assess NMF (Hamilton, 2009; Mooney et al., 2013; Roe et al., 2015; Rowell, Aughey, Hopkins, Stewart, & Cormack, 2016; Taylor, 2012), with effectiveness of CMJ confirmed by Gathercole, Sporer, Stellingwerff, et al. (2015a). This SSC assessment, when utilising CMJ, can help guide practitioners upon player restoration and recovery in the days post-match. Evidence showing lack of restoration post rugby union match play was presented by McLean (2010), who reported that CMJ variables did not return to baseline values until four days after matches, while West et al. (2014) noted that peak power, measured via CMJ, recovered no sooner than

60 hours post rugby union match play. Further support for jump testing to measure fatigue was presented by Twist et al. (2012) within elite level rugby league, who reported that CMJ provided the most appropriate indirect marker of both tissue damage and reduction in muscle force generating capacity. Reductions in jump performance are often caused by a change in calcium release per action potential, which leads to impairment of excitation-contraction coupling and the associated LFF. This resultant LFF has an impact upon players' jump performance potential, post muscle damaging exercise such as rugby union (Skurvydas, Jascaninas, & Zachovajevs, 2000), and therefore supports CMJ assessment post-match to measure fatigue.

CMJ is a jump method that is less likely to carry the variability of technique observed in other jump methods, as reported in Chapter 4.4. Further investigation into assessing the variability of a single CMJ performance, post rugby union match, is therefore required. Results from the previous chapter (Chapter 5) would support this view, where it was noted that CMJ exhibited high reliability between-session when compared to SJ and SLDJ. The results from Chapter 5 involved two jumps per trial, yet due to time constraints within elite team sport settings, the likelihood of being able to perform multiple jumps within a daily assessment of readiness is unrealistic. Due to these "real world" limitations, a single measure of CMJ performance that measures jump height alone is perhaps a more realistic tool for performance assessment. CMJ displays relevance to rugby specific movements, which, when combined with its ease of administration within regular gym based sessions, make it a commonly preferred assessment tool for NMF. Support for the use of a sole CMJ was noted by Cormack, Newton, McGuigan, and Cormie (2008), who showed that singular CMJ flight time presented more substantial reductions in performance compared to five repeated CMJs, suggesting that repeated jumps make it less able to distinguish between levels of neuromuscular function despite their reactive nature and SSC involvement.

As a result of many practitioners' inability to conduct multiple jump tests pre-training and the unreliable nature of between-session testing noted for SJ and SLDJ as noted in the Chapter 4, this study aimed to assess the reproducibility between sessions of the performance of one CMJ. This study will also determine if the use of one CMJ (jump height) is sufficient for use in future research and identify SWC between sessions. The identification of the most reliable measures of testing for use in field settings, rather than in controlled laboratory conditions, was noted by Hopkins et al. (2012). As previously researched (Hopkins et al., 2012), measures that provide the smallest typical error and are also practical for use within elite team sport field settings are key. A jump test such as a single CMJ needs sufficiently high reliability for use in research, which assesses small but important changes in performance, although its practicality for use in the field is also of importance. It was hypothesised that a single CMJ would be a reliable jump modality for assessing between-sessions performances. Results from this study will inform practitioners about the reliability of a single CMJ and the resultant measurement error and in addition will assess an individual's ability to replicate performance.

6.3 Method

6.3.1 Participants

Twelve elite rugby union players (age 28.0 ± 5.2 years, training age 9.0 ± 4.9 , height 183.6 ± 5.1 cm, mass 97.9 ± 12.3 kg), from the same professional rugby club, volunteered for the study. Participants were all healthy and active individuals who had no current injury issues. All subjects provided written informed consent to participate and Salford University Research and

Ethics Committee approved the study. The sample size used within this study was considered satisfactory in accordance with guidelines provided by Hopkins (2000).

6.3.2 Procedure

This study assessed between-sessions reliability of a single CMJ across two testing sessions. Testing sessions were separated by no longer than fourteen days for all players and the training weeks throughout the testing period were standardised. Players wore appropriate footwear for each jump and were given the same verbal instructions prior to each attempt. Despite the testing being conducted post-match, the influence of games was considered to be unlikely to have an influence upon results, as the time-points of assessment were consistent throughout this study and the training and match protocol prior to testing commencing on each occasion was standardised.

6.3.2.1 Instrument

The instrument used to assess jump height within this research was the *OptoJump* (Microgate, Bolzano, Italy), previously reported in more detail within chapter 4.3.3.1. Players stood between the *OptoJump* bars when jumping, with jump height assessed via flight time.

6.3.2.2 Countermovement Jump (CMJ) technique

The CMJ was performed from a standing position, with the whole plantar part of the foot touching the jumping surface with the hands resting on the hips. A counter movement was conducted by the participant, until the knee angle reached approximately 90°, then immediately the participant jumped as high as they could, with their legs remaining straight upon flight, therefore preventing any tucked legs which would lead to inaccurate measurement. Upon landing, the participants made contact with the testing surface, with knees extended and only flexing to absorb the impact once contact had been made with the floor. Flexing of the knees or the hips delays contact with the mat and therefore distorts flight time. Prior to each jump the participant was encouraged to jump as high as possible. Post-jump, participants received verbal feedback about their performance.

6.3.2.3 Jump Height and Flight Time

Jump height was calculated via flight time using the following equation utilised by Byrne and Eston (2002), adapted from that proposed by Bosco et al. (1983).

$$\text{Jump Height} = (9.81 \times \text{flight time}^2) / 8$$

6.3.3 Statistical Analyses

All statistical analysis was conducted on SPSS for windows, with an *a priori* alpha level set at $p < 0.05$. Between-session reliability was determined using both ICC (Model 3, 1) and Paired samples T tests. In accordance with Rhea (2004), Cohen's *d* effect sizes (ES) were interpreted as follows; trivial = < 0.25 , small = $0.25 - 0.5$, moderate = $0.50 - 1.0$ and large > 1.0 . Post-hoc statistical power was calculated using G Power 3.1 (Faul et al., 2009), for a large effect size of 0.5, a total $n = 7$ was sufficient to deliver an actual power of 0.49. The reliability was considered acceptable if the ICC $r \geq 0.8$ (Cortina, 1993). SEM and smallest detectable differences (SDD) were calculated to provide information for upon whether or not a change in an individual's performance was significant, with SEM calculated using the formula: $\text{SD}(\text{pooled}) * (\sqrt{1 - \text{ICC}})$ and SDD calculated from the formula: $(1.96 * (\sqrt{2})) * \text{SEM}$.

6.4 Results

6.4.1 Between-session reliability of a single CMJ per testing day

Between-session reliability was high for the CMJ (ICC = 0.986; $d = 0.153$; SEM 0.003; SDD = 0.01, 2.4%) (Figure 6.1), with trivial and non-significant differences ($p > 0.05$) noted between days.

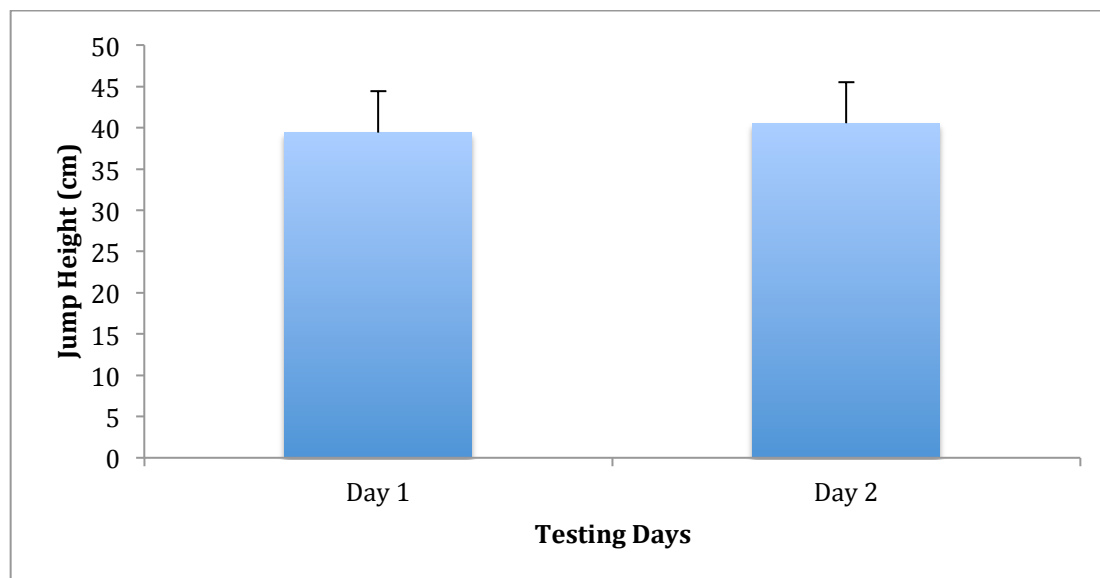


Figure 6.1: CMJ height for testing days one and two

6.5 Discussion

As was hypothesised, a single CMJ can be considered to be a reliable jump modality for assessing between-sessions performances. Results from this study followed a similar pattern to that reported in Chapter 4 and 5, with a single CMJ measured via *OptoJump* appearing as highly reliable ($r = 0.906$) between sessions. Despite Chapter 4 showing differences existed between session one and session two, when assessing CMJ performance, this particular investigation shows a contrary view: that the performance of a single CMJ (measuring jump height) is a reliable measure for assessing post-match levels of readiness.

Support for the reliability of *OptoJump* has previously been reported by Glatthorn et al. (2011), who noted very high ICCs for both *OptoJump* CMJ height and CMJ height measured on a force plate, despite systematic differences occurring between instruments (-1.06 cm; $p < 0.001$). Glatthorn et al. (2011) noted excellent test-retest reliability of the *OptoJump* CMJ height measurement (ICC 0.989; CV 2.2%). However, the jump protocol implemented between this experimental study and that of Glatthorn et al. (2011) differs, whereby, for example, the subjects used were not considered to be elite within the research by Glatthorn et al. (2011), meaning that, as a result, clear comparisons should not be made. The misalignment of the photoelectrical cells associated with the *OptoJump* could also have explained some of the differences observed, such as the concern that a subject's foot might have broken the electrical cell, but not yet landed on the force plate. Similarly, when assessing reliability of jump measures, Jensen et al. (2011) presented high reliability (ICC 0.966; CV 5.1%) for *OptoJump* using the flight time calculation reported earlier (Chapter 5.3.2.3). When considering that the

research by Jensen et al. (2011) involved similar methodology and perhaps most importantly, rugby union players, comparisons between these results are warranted.

More recent research specifically assessing CMJ performance within rugby players by Gathercole, Sporer, and Stellingwerff (2015) is also of interest. Gathercole, Sporer, and Stellingwerff (2015) noted that flight time and peak displacement corresponded with increased training load. One might therefore assume that the results by Gathercole, Sporer, and Stellingwerff (2015) indicate that jump height decreased alongside increases in training volume, yet the opposite is true. It is interesting for practitioners to note that there was an absence of change in the jump height variable itself. Results from the research by Gathercole, Sporer, and Stellingwerff (2015), assessing the response of CMJ performance to increases in training load in elite female rugby players, cannot be compared to the absolute CMJ values presented in this study, as both the gender of the subjects and fatigue created differ. Readers are also advised to note that the assessment of jump height used within the research by Gathercole, Sporer, and Stellingwerff (2015) incorporated a different testing protocol and that the assessed data was taken from within training periods and not from testing post-match play, as was the case in this study.

As reported in Chapter 5, when assessing two CMJ performances using the *OptoJump*, a SDD of 1.7% was noted to be of interest to practitioners working in the elite rugby environment. Data from this study also adds to the knowledge base, with, for example, the value of 2.4% change for a single CMJ being smaller than the value reported by Glatthorn et al. (2011). Glatthorn et al. (2011) noted high ICC values (mean 0.986), low coefficient of variation (2.5%) and low random errors averaged (2.87 cm), therefore supporting CMJ as reliable for detecting changes in longitudinal assessments. When trying to identify NMF using CMJ, jump height, assessed from flight time using the force plate, has been considered the most precise and reliable, yet as previously explained in Chapter 5, for most team-based scenarios a force plate is not readily available. When considering the financial outlay associated with force plate use, the likelihood of rugby clubs being able to implement such technology is unlikely; therefore the *OptoJump* would be the next best alternative. This study adds to the knowledge base by identifying a difference of greater than 1 cm (2.4%) in jump height signifying meaningful change between sessions, while recommending the assessment of a single CMJ performance.

6.5.1 Limitations of this study

One potential limitation of this research surrounds the relatively small sample size ($n=12$). Despite the sample size being larger than those used in the investigations reported in Chapters 4 and 5, an even larger sample size would perhaps have presented greater depth and breadth to the knowledge base of a sole CMJ. Alongside sample size, another potential limitation of this study surrounds the self-selected CMJ protocol of the players. Players were noted potentially to have adopted differing CMJ techniques, mainly whereby depth of CMJ on the downward phase varied and width of stance was individually selected. These individually selected jump techniques could, therefore, have altered results. It could, however, be argued that the variability in CMJ technique improved the ecological validity of this study, as not all players would normally move in the same manner especially during the competition phase of an elite rugby union playing season. Fatigue and physical mobility issues due to the physical nature of the games and the training that the players undertake, are factors that can commonly influence movement and technique.

6.6 Practical Applications

From this research, one could conclude that a learning effect does not exist between testing days for performance of a single CMJ. As a consequence, contrary to the views of past research a single CMJ measured via *OptoJump* appears to be a highly reliable measure of assessing between-sessions performances. Future practice recommends a meaningful change of 2.4% (1 cm) as being of note for practitioners working in the elite rugby environments, when assessing CMJ performance between sessions. This study therefore adds to the knowledge base existing for between-session assessments of CMJ performance in elite rugby union players, supporting the *OptoJump* as the next best alternative for assessing a single CMJ performance when force plates are not available.

6.7 Implications of experimental chapter 6 for subsequent studies

Despite this chapter firstly confirming the reliability of conducting one CMJ in the days between matches and secondly identifying a meaningful change of 2.4% (1cm), a greater understanding of the time-course of restoration of CMJ in the days post rugby match is needed. The ability for applied practitioners to be able to quantify both magnitude and duration of performance decrement would be of major benefit for training prescription in the days post match. In addition to the assessment of CMJ height as a measure of performance, a need also exists to assess another measure of post-match recovery, to provide further confidence to future CMJ height investigations.

7 Change in Countermovement Jump Performance and Well-being Scores of Professional Rugby Union Players Post-match

7.1 Abstract

Planned periodisation without consideration for restoration of performance and testing of time-course of recovery is likely to put players at risk of sub-optimal performance or injury risk. Stress on rugby players' bodies is often more frequently accumulated by game situations, where players are asked to compete on a weekly basis. CMJ and self-report well-being (WB) testing protocol is commonly used within elite field sport settings in order to assess NMF and perceived fatigue, when performance is impaired in the immediate days post-match. This study aimed to compare CMJ performance and WB scores at pre-match and three time-points post-match (60 hours, 90 hours and 170 hours), in order to develop a better understanding of time-course of recovery in elite level rugby union across positional groups. Relationships between changes in CMJ performance, WB scores and match characteristics (total distance covered, distance covered in Zone 5, distance covered in Zone 6, accelerations, decelerations and impacts encountered in Zones 4, 5 and 6) were also investigated across positional groups. Differences in CMJ and WB across time-points were determined using repeated measures ANOVA with Bonferroni post-hoc analysis, or non-parametric equivalent, illustrating that both CMJ performance and WB score were reduced at 60 hours post-match, 90 hours post-match and 170 hours post-match, with WB score reduced to a greater value and for a longer time-course than CMJ. A meaningful change of 2.6 cm (-6%) change in CMJ performance was noted alongside a -9% change in WB score at 60 hours post-match. In addition, correlations were strong and significant between total distances covered ($p = 0.002$; $r = 0.396$), decelerations ($p < 0.001$; $r = 0.532$), D5 ($p < 0.001$; $r = 0.488$) and D6 ($p < 0.001$; $r = 0.489$) at 60 hours post-match with changes in CMJ performance. Further correlations were noted between accelerations ($p = 0.001$; $r = 0.558$) at 60 hours post-match with changes in CMJ performance for the forwards only. The data from this study adds to the knowledge relating to changes in CMJ performance and self-reported WB post-match in rugby union, although the evidence from this study would dispute the views of previous time-course research, when considering the longer time-course of recovery associated with backs compared to forwards.

7.2 Introduction

Rugby union has been reported to involve both intense anaerobic exercise interspersed with lower intensity bouts of aerobic exercise, with match distances averaged across a season being 5850 ± 1101 m for forwards and 6545 ± 1055 m for backs per game (Cahill et al., 2013). The high level of impacts (> 795 per game) and the metabolic cost (work to rest ratios of greater than 1:4) involved in a sport such as rugby union are contributing factors towards the physiological and mechanical stress associated with EIMD (Austin et al., 2011a; Roberts et al., 2008). EIMD. Additionally, the associated time-course of recovery has been extensively researched (Hauswirth et al., 2011; McLellan & Lovell, 2012; Twist & Eston, 2009; Twist & Sykes, 2011), with correlations noted between the total number of impacts experienced within elite rugby league match play and compromised neuromuscular function, when assessing jump performance in the 48 hours post-match (McLellan & Lovell, 2012).

A typical professional rugby season in the northern hemisphere contains over 30 games and involves blunt force trauma and high running volumes in training and matches (Alaphilippe et al., 2012). The volume and intensity of work, including associated trauma from contact completed in a rugby union match, result in fatigue and extended recovery time post-match, with West et al. (2014) noting that peak power, measured via CMJ, recovered no sooner than 60 hours post-match. Due to blunt force trauma and high running volumes from both training and games over the course of a playing season, rugby players become fatigued (Argus, Gill, Keogh, et al., 2012; Cresswell & Eklund, 2006; Fuller et al., 2007). As reported by Gill et al. (2006), the presence of residual fatigue, carried over from the previous games and training, is represented by increased creatine kinase (CK) levels, with reductions in performance measures also being reported (Crewther et al., 2009). It is, however, important for practitioners to note that restoration of performance measures is of utmost importance for athletes and that this must be achieved prior to subsequent competition, irrespective of biochemical markers. In essence, restoration of performance is perhaps more important than any residual biochemical disruptions, as the ability of rugby players to be able to perform their role within match play is paramount. Biochemical disruption may be evident upon assessment of rugby players in the days post-match (Crewther et al., 2009; Lindsay, Lewis, Scarrott, Gill, et al., 2015; Smart et al., 2008; Takarada, 2003; West et al., 2014), although if this biochemical imbalance is not affecting a player's ability to perform optimally, then surely this is of less of a concern than a lack of restoration of performance measures, which potentially signify an inability to execute optimal performance, despite fatigue being present in both cases.

Intense exercise, such as rugby union match play, has been shown to cause temporal impairments in immune function, with disturbances in immunity lasting up to 38 hours post-match (Cunniffe et al., 2010). Frequently, the greatest physical stimuli of a rugby player's week is the match, yet high training loads combined with match exertions and insufficient recovery have been reported in rugby, often pushing players into states of overreaching with resultant reduced neuromuscular function (Coutts, Reaburn, Piva, & Murphy, 2007). Recent research from rugby union (Jones et al., 2014) supports the view that muscle damage is position-specific, with the number of impacts encountered during a match relating directly to the levels of muscle damage, indicated by increased levels of (CK). Mashiko et al. (2004b) noted that the blunt trauma associated with match demands performed by forwards may produce longer lasting muscle damage than that experienced from eccentric actions, which backs would be more likely to encounter. As was illustrated in previous research (Reardon, Tobin, Tierney, & Delahunt, 2016), forwards are more likely to incur contacts during match-play, with recent research by Roe et al. (2017), noting increased likelihood of upper body NMF, reduced well being and greater elevations in CK post training sessions involving contact than sessions without contact.

Further evidence of match contacts and resultant fatigue was noted by Twist et al. (2012), where total contacts for forwards was reported to correlate with all markers of post-match fatigue (muscle soreness $r = 0.62$; perceived fatigue $r = 0.69$; CK $r = 0.74$; jump flight time $r = -0.55$), yet only flight time was correlated with offensive contacts in backs ($r = 0.54$). This research by Twist et al. (2012) used time-motion analysis to assess contacts encountered by professional rugby league players, reporting that backs presented greater decrement in performance than forwards, when assessing changes in CK, perceptual and neuromuscular fatigue 48 hours post-match. The influence of concentric and eccentric forces during match play, upon resultant muscle damage, was also presented by Jones et al. (2014), who reported

that high speed running was a predictor of muscle damage for backs. These high-speed running involvements are likely to include deceleration and accelerations, which, when considered alongside the findings from Chapter 3 (that backs encounter a greater frequency of these match demands compared to forwards) is an important consideration for future time-course of restoration research. The research presented above, therefore, highlights the importance of looking at the relationships between match characteristics that assess positional differences and the muscle damage response created, with high level impacts and high speed running being the main areas of focus.

Prior research has illustrated the negative influence of high intensity rugby specific activities, such as sprinting and collisions along with the resultant muscle damage response (Jones et al., 2014; McLellan & Lovell, 2012; Morel et al., 2015). In addition, from the evidence gathered in Chapter 3 it was noted that total distance covered, high intensity running zones and impacts in higher zones are likely to have an influence upon delayed restoration of performance post-match. When considering the research by McLellan et al. (2011a) showing impacts in higher zones (> 8.1 G) were positively correlated with significant muscle damage, and the research by Jones et al. (2014) showing correlations between high speed running (> 5 m.s⁻¹) and sprinting (> 5.6 m.s⁻¹) and increased plasma CK, the need to further investigate specific GPS metrics is warranted. The influence of specific match demands (specifically the high intensity metrics) are therefore of interest to practitioners, when assessing restoration levels post rugby union match play across positional groups. High force muscle contractions such as those experienced in accelerations, decelerations and collision situations (which are likely to be associated with impacts in Zones 4, 5 and 6) are assumed to result in greater decreases in performance, and therefore also warrant investigation.

An accumulation of training stress, if managed properly, will have a positive effect upon the athlete, however, if managed poorly and insufficient recovery occurs, FOR can develop into the more severe training response phenomenon of OT. Subjective measures, specifically, have been used to monitor fatigue in previous research, including self-report well-being questionnaires showing reduced perception of restoration across a longitudinal period (Cresswell & Eklund, 2006), with correlations between OT scores assessed via questionnaire and altered CK values apparent in the study by Alaphilippe et al. (2012), which assesses biochemical markers over a longitudinal period in rugby union. Neuromuscular function tests are perhaps the most commonly used forms of assessing player fatigue in team sport settings; and include varying forms of jump tests, plyometric push-ups, sprint performances, sub-maximal and maximal performance tests and isokinetic dynamometry (Duffield et al., 2012; Johnston et al., 2013; Twist & Sykes, 2011). Decreased jump performance has been reported for up to 24 hours, with a reported 26% reduction in PRFD (McLellan et al., 2011b; Twist et al., 2012).

Despite the use of a rugby specific activity being the most likely activity to indicate readiness in the immediate days post-match, its practicality for use within a weekly training cycle is unrealistic. Many studies (Gathercole, Sporer, & Stellingwerff, 2015; Johnston et al., 2015; McLellan et al., 2011d; West et al., 2014) assessing rate of recovery post fatigue in rugby have, therefore, assessed restoration of performance through using tests that are reproducible and do not induce added fatigue. In an assessment of multiple tests (CMJ and 20 m sprint), to detect NMF post fatiguing exercise with team sport athletes, Gathercole, Sporer, Stellingwerff, and Sleivert (2015b) noted moderate reductions in CMJ at 72 hours, while 20 m sprint performance showed no reduction, therefore recommending their use. One aim of this research was to

compare CMJ performance and WB scores pre-match and 60 hours (post-match), 90 hours (post-match) and 170 hours (post-match), in order to develop a better understanding of time-course of recovery post-match in elite level rugby union. Secondly, this research aimed to determine whether or not there were differences in CMJ performance and WB scores; baseline, 60 hours (post-match), 90 hours (post-match) and 170 hours (post-match) and also between positional groups (forwards and backs) as a result of the match demands specific to these groups. Thirdly, this research aims to assess changes in CMJ performance and WB performance between positional groups (forwards and backs), GPS variables used to assess the influence of specific match demands upon restoration of performance. In line with the previous research (McLellan & Lovell, 2012; McLellan et al., 2011b; Twist et al., 2017; Twist & Sykes, 2011; Twist et al., 2012; West et al., 2014), it was hypothesised that delay of restoration of CMJ performance and reduced WB scores would be present in the immediate days post-match, and that forwards would take longer to recover from match demand than backs. Relationships between changes in CMJ performance, WB scores and match characteristics (Total distance covered, distance covered in Zone 5 and 6, accelerations, decelerations and impacts encountered in Zones 4, 5 and 6) were also investigated. Only these match variables were investigated, as these metrics were considered to be important for further investigation, in light of research outlined above (Lindsay, Lewis, Scarrott, Gill, et al., 2015; McLean et al., 2010; McLellan et al., 2011a, 2011b; Roe et al., 2017).

7.3 Method

This study focused upon two measures; neuromuscular function (CMJ height) and subjective self-report well-being (WB). These test measures were then related to GPS data (Total distance covered, accelerations, decelerations and impacts encountered in Zones 4, 5 and 6), in order to assess the effect of game demands upon subsequent CMJ performance and WB at 60 hours, 90 hours and 170 hours post-match. Comparisons were made baseline to determine if these variables had returned to normal prior to the start of the next match.

7.3.1 Participants

Twenty-seven subjects (Age 27.7 ± 4.6 years, training age 8.4 ± 4.7 years, bodyweight, 98.1 ± 11.2 kg and height being 184.3 ± 6.3 cm) were assessed across five games resulting in fifty-nine data sets, with some players presenting data from more than one game. Of the 59 data samples, forwards represented 31 instances, while the backs represented 28 instances. All participants were taken from within the professional training squad at the participating rugby club.

7.3.2 Experimental Approach

This study was conducted in accordance with the Declaration of Helsinki and was approved by Salford University Institutional Review Board. The seven-week assessment period covered five games and was taken during a competitive phase of a rugby union playing season. Throughout the seven-week period, no coach-led recovery strategies were administered upon the participants, such as ice baths, to aid restoration of performance. Any recovery methods utilised by the participants were noted and taken into account for further analysis. Participants were advised to maintain their usual recovery process post-match throughout the testing period, including nutritional interventions or active swim recovery sessions.

Throughout the testing period, training volume was consistent between games; on average, each week consisted of two resistance-training sessions and five rugby sessions. As commonly seen within team sport settings, where games are weekly, training volume tapered as game day

approached. For the performance testing analysis, only players who completed over 30 minutes of matches were included. Thirty minutes was considered to be an appropriate game-time exposure for players to experience trauma and fatigue that might affect the performance measures assessed. As illustrated by research outlined in Chapter 1 of this thesis and from the results recorded in Chapter 3, elite rugby players are likely to be substituted at varying time points, depending upon positional group (Forwards 50-65 mins; Backs 70-75 mins), with these varying times, therefore, being likely to affect restoration of performance levels post-match.

Due to the structure of the training weeks associated with this study, performance tests were measured at pre-match, 60 hours post-match, 90 hours post-match and at 170 hours post-match (prior to the subsequent match). Pre-match tests were considered the baseline upon which to compare the post-match values against, with tests conducted approximately three hours prior to kick off. These time-points were chosen as they were the only available time-slots that could be consistently assessed across this study and in addition were considered to be a consequence of “real world” testing in the elite sport environment, where training schedules often change post-match.

7.3.3 Jump testing

The CMJ was selected in line with previous research (Johnston et al., 2015; Johnston, Gabbett, et al., 2014; McLean et al., 2010; McLellan & Lovell, 2012; McLellan et al., 2011b; Twist et al., 2012; West et al., 2014) in order to measure neuromuscular performance and was performed from a standing position, with the whole plantar part of the foot touching the jumping surface and the hands resting on the hips throughout. A counter movement was conducted by the participants until the knee angle reached approximately 90°, then immediately the participants jumped as high as they could, with their legs remaining straight upon flight, therefore preventing any tucked legs which would lead to inaccurate measurement. Upon landing the participants made contact with the testing surface with a knee angle extended to 180° and flexed upon contact with the surface. Post-jump, each participant received verbal feedback about his performance, with only one jump being allowed for each individual due to time constraints. This was not considered to be an issue as all individuals were familiar with CMJ protocol. In line with previous studies assessing CMJ performance, protocols such as hands on the hips throughout the jump and extended feet throughout flight to prevent tucking of the knees, were administered, as these alternative techniques have been reported to cause inaccuracies (Flanagan et al., 2008; Taylor, 2012). All CMJs were performed at a depth at which the subjects were comfortable and they were instructed to “jump as high as possible”. CMJ was performed without arm swing, as an increase in jumping height of 10% has been observed when countermovement jumping with arms is performed compared to without arms (Lees et al., 2004). All jumps were performed on an *OptoJump* optical measuring system (Microgate, Bolzano, Italy), previously reported in more detail within Chapter 4.3.3.1. Players stood between the *OptoJump* bars when jumping, with jump height assessed via flight time.

7.3.4 Self-report well-being questionnaires

All players completed a WB questionnaire upon waking in their own homes, using an online player management tool. This questionnaire assessed WB via the players’ subjective responses to questions around their sleep, muscle soreness, mood and appetite. The questionnaire structure was based upon the recommendations of Hooper and Mackinnon (1995) and was completed on every training day throughout the testing period. The WB questionnaire used within this research was one that was familiar to the participants and was completed at the

same time-points to try and ensure reliability, consistency and reproducibility. WB assessment was scored out of ten, with zero being poor and ten being good. A sample questionnaire can be found within Appendix A. Despite WB assessment being regularly implemented in many rugby specific scientific studies and considered to be easy to implement, the reliability of WB use is yet to be assessed. The main reason behind the lack of academic research to support WB use surrounds the notion that self-report subjective WB is difficult to quantify. In order to measure the reliability of WB questionnaires subjects would have to complete a structured WB assessment on more than one occasion within a short space of time. However, this would perhaps be deemed difficult to control, as subjects could potentially deliberately remember what they had completed in the prior assessment and replicate it, therefore questioning the reliability of the data collected.

7.3.5 Match analysis and GPS data

Analysis of GPS data and associated training volume (distances, speeds and impacts for example) has been utilised in many studies of rugby union (Austin et al., 2011a; Cahill et al., 2013; Coughlan et al., 2011) and is considered an essential tool of many elite sport team practitioners.

Measurements were conducted on players from one club, with GPS units (*StatSports Viper*, Northern Ireland) being used throughout all games to assess movement patterns, sampling at a 10 Hz frequency. Reliability of GPS analysis in team sport settings has been confirmed in many previous studies (Coutts & Duffield, 2010; Cummins et al., 2013; Johnston, Watsford, et al., 2014; Varley et al., 2012), with it's worth outlined in greater detail in Chapter 2.1.2. The indices assessed from the GPS data were; total distance covered, distance covered in Zone 5, distance covered in Zone 6, accelerations, decelerations and impacts encountered in Zones 4, 5 and 6. All participants took part in normal training weeks, prescribed by the staff, with no training being altered for the purpose of this study.

Table 7.1: Categorisation of distances covered and impacts

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Speed (m/s)	0 – 1.5	1.51 – 3.0	3.01 – 4.0	4.01 – 5.5	5.51 – 7.0	7.01 +
Speed (km/h)	0 – 5.40	5.41 – 10.80	10.81 – 14.40	14.41 – 19.80	19.81 – 25.20	25.21 +
Impacts in Zones (G)	3 – 5	5 – 7	7 – 9	9 – 11	11 – 13	13 – 15

For the purposes of discussing the distance and impact zones, shorthand abbreviations were used. D5 related to distance covered in Zone 5, D6 to distance covered in Zone 6. Similarly, impact zones were abbreviated to Im4 for impacts encountered in Zone 4, Im5 for impacts encountered in Zone 5 and Im6 for impacts encountered in Zone 6.

7.3.6 Statistical Analyses

Statistical analysis was performed using SPSS Version 20 (IBM), with an *a priori* alpha level set at $p < 0.05$. Distributions of analysed variables were assessed using Shapiro Wilk test. Two separate repeated measures ANOVA's with Bonferonni post-hoc analysis were conducted to determine changes in CMJ performance and WB scores at 0, 60, 90 and 170 hours (immediately prior to next game). Effect sizes (ES) were also determined using the Cohen's *d* method, and interpreted based upon the criteria suggested by Rhea (2004) and interpreted as follows; trivial = < 0.25 , small = $0.25-0.5$, moderate = $0.50-1.0$ and large > 1.0 .

Relationships were assessed amongst the whole data set and separately for forwards and backs; in order to determine associations between GPS match performance data and change in CMJ performance and WB score (Pre-match score – post-match score). Correlations were made using both parametric and non-parametric equivalents, where appropriate. When multiple correlations were made, the p value was calculated via Bonferonni post-hoc analysis in order to determine the true significance. Associations were also assessed separately for forwards and backs, as a result of the data presented in Tables 3.4 and 3.5 within Chapter 3.4.2 along with those presented in prior research (Cahill et al., 2013; Coughlan et al., 2011; Cunniffe et al., 2009; Jones et al., 2015; Lindsay, Draper, et al., 2015; Roberts et al., 2008), thus illustrating differences in match characteristics between forwards and backs across many metrics (distance covered, accelerations, decelerations, distance in Zone 6 and Impacts in Zone 6).

7.4 Results

7.4.1 Changes in CMJ performance pre to post-match

Shapiro-Wilk tests of normality revealed that CMJ (jump height) was normally distributed at time-points baseline, 60 and 170 hours post-match ($p > 0.05$), but not at 90 hours post-match ($p = 0.012$). Alongside absolute values, relative values also demonstrated normal distribution via Shapiro-Wilk tests, when assessing the percentage change in CMJ (jump height) at time-points baseline, 60, 90 and 170 hours post-match ($p > 0.05$). As a result, a Friedman test was conducted showing a significant difference in jump height across time-points ($p = 0.000$), with multiple Wilcoxon tests with Bonferonni correction demonstrating a small yet significant decrease between CMJ performance pre-game (baseline = 39.9 ± 5.3 cm) and 60 hours (37.3 ± 4.8 cm, $p = 0.000$, $d = 0.51$), 90 hours (37.1 ± 5.3 cm, $p = 0.000$, $d = 0.52$) and 170 hours post-match (38.7 ± 5.1 cm, $p = 0.015$, $d = 0.23$) (Figure 7.1). CMJ performance at 60 hours (37.3 ± 4.8 cm) was significantly lower than at 170 hours post-match (38.7 ± 5.1 cm, $p = 0.045$, $d = 0.28$), with a significance difference also noted between 90 hours post-match (37.1 ± 5.3 cm) and 170 hours post-match (38.7 ± 5.1 cm, $p = 0.003$, $d = 0.30$). No significant ($p > 0.05$) or meaningful ($d = 0.039$) difference was noted between 60 hours and 90 hours post-match.

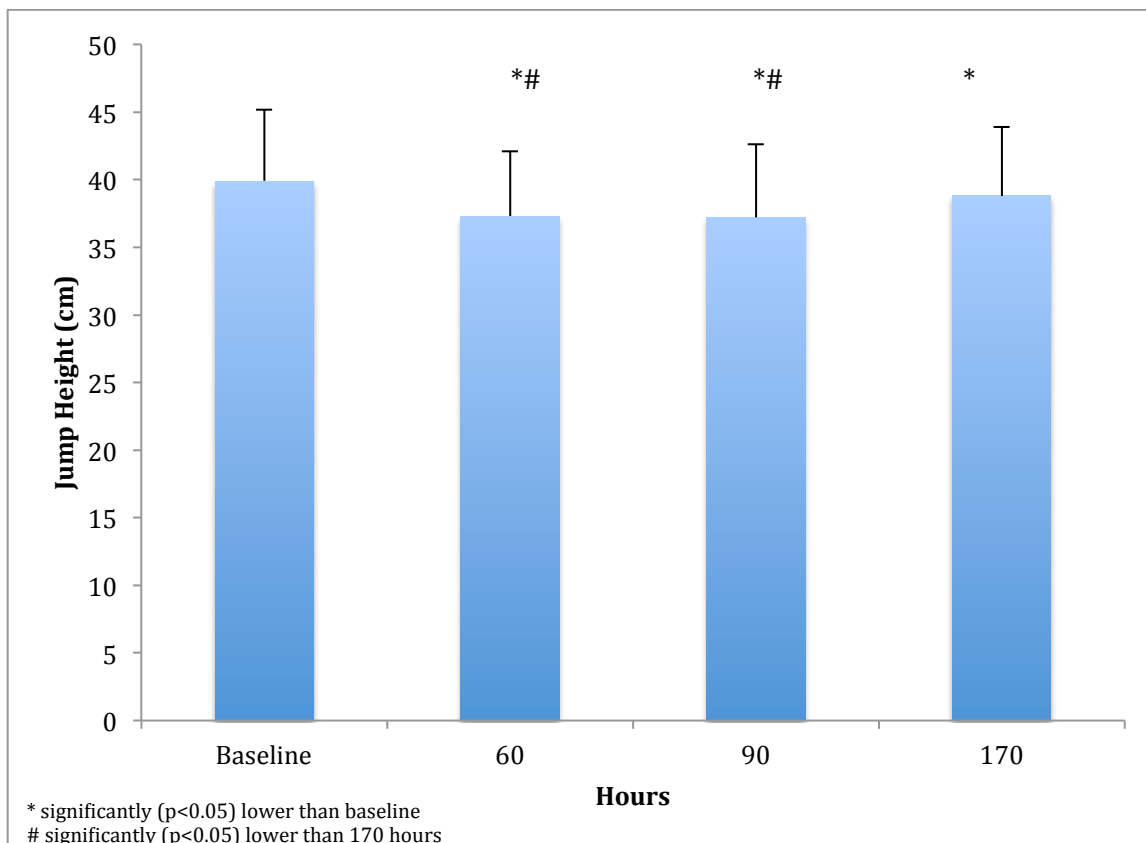


Figure 7.1: Comparison of CMJ performances pre and post-match (n=59)

7.4.2 Changes in WB performance post-match

In contrast to CMJ, Shapiro-Wilk tests of normality revealed that WB (total score) were normally distributed at all time-points ($p > 0.05$). Alongside absolute values, relative values also demonstrated normal distribution via Shapiro-Wilk tests, when assessing the percentage change in WB score at time-points baseline, 60, 90 and 170 hours post-match ($p > 0.05$). As a result, RMANOVA tests revealed that WB scores were significantly different ($p < 0.001$), when comparing baseline (3.77 ± 0.47) to 60 hours (3.43 ± 0.54) ($p < 0.001$, $d = 0.67$), 90 hours (3.40 ± 0.52) ($p < 0.001$, $d = 0.74$) and 170 hours (3.65 ± 0.58) ($p < 0.001$, $d = 0.22$) post-match, yet not between 60 and 90 hours ($p < 0.05$, $d = 0.05$). In addition, significant differences were noted between 60 hours and 170 hours post-match ($p < 0.001$, $d = 0.39$) (Figure 7.2).

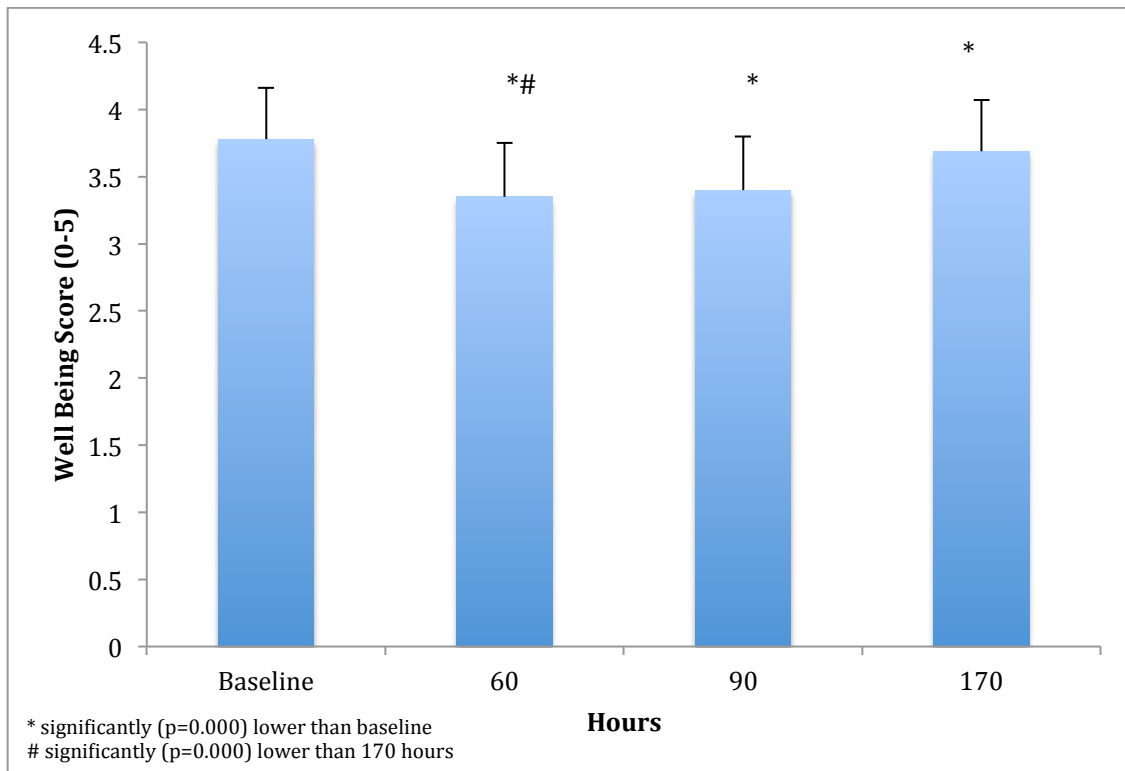


Figure 7.2: Changes in wellbeing scores pre to post-match (n=59)

7.4.3 A comparison of changes in CMJ performance pre and post-match between forwards and backs

Friedman test showed no significant difference in jump height for forwards across time-points ($p > 0.05$) (Baseline 36.9 ± 0.82 cm; 60 35.7 ± 0.97 cm; 90; 35.4 ± 1.06 cm; 170 hours 36.7 ± 0.94 cm). In contrast, Friedman test showed a significant difference in jump height for backs across time-points, with multiple Wilcoxon tests and Bonferonni correction demonstrating a significant decrease in CMJ performance between baseline (43.2 ± 3.9 cm) and 60 hours (39.0 ± 3.2 cm, $p < 0.000$, $d = 2.30$), 90 hours (39.1 ± 3.9 cm, $p < 0.000$, $d = 2.57$) and 170 hours (41.0 ± 3.9 cm, $p = 0.005$, $d = 1.57$). Additionally, for the backs, CMJ performance was significantly ($p = 0.010$, $d = 0.53$) lower at 90 hours compared to 170 hours post-match, although no significant differences ($p > 0.05$) were noted between 60 and 90 hours post-match and 60 and 170 hours post-match (Figure 7.3).

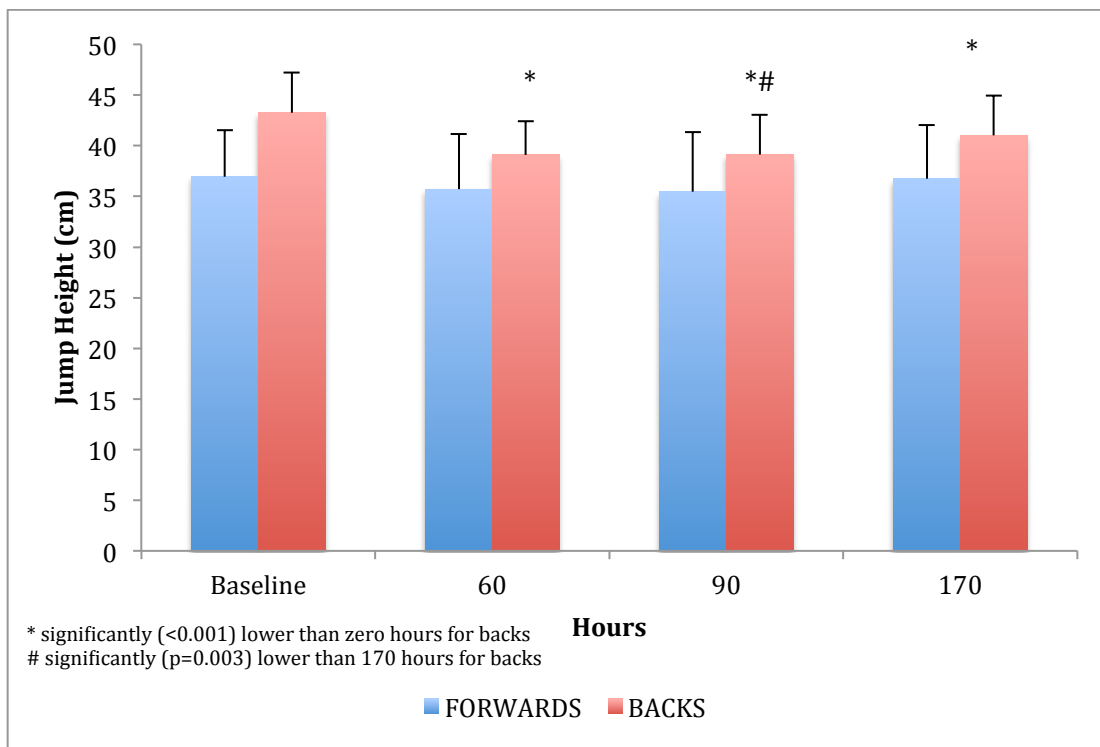


Figure 7.3: Changes in CMJ performance pre to post-match (Forwards n=31; Backs n=28)

7.4.4 A comparison of changes in WB performance pre and post-match between forwards and backs

RMANOVA revealed that WB scores for forwards were significantly different between baseline (3.7 ± 0.3) and 60 hours (3.4 ± 0.3 ; $p < 0.001$, $d = 1.00$) post-match and between baseline and 90 hours (3.4 ± 0.4 ; $p < 0.001$, $d = 0.84$) post-match, yet no significant differences were noted ($p > 0.05$) between baseline (3.7 ± 0.3) and 170 hours (3.7 ± 0.3) post-match and between 60 hours (3.4 ± 0.3) and 90 hours (3.4 ± 0.4) post-match (Figure 7.4). Additionally, forwards showed significant differences between 60 hours (3.4 ± 0.3) and 170 hours (3.7 ± 0.3 ; $p < 0.001$, $d = -1.00$) post-match and between 90 hours (3.4 ± 0.4) and 170 hours (3.7 ± 0.3 ; $p = 0.005$, $d = -0.84$) post-match. Backs also showed significantly different WB scores between baseline (3.7 ± 0.4) and 60 hours (3.3 ± 0.4 ; $p < 0.001$, $d = 1.00$) post-match, baseline (3.7 ± 0.4) and 90 hours (3.3 ± 0.3 ; $p < 0.001$, $d = 1.13$) post-match and baseline (3.7 ± 0.4) and 170 hours (3.5 ± 0.5 ; $p = 0.023$, $d = 0.44$) post-match, yet no significant differences were noted ($p > 0.05$) between 60 hours (3.3 ± 0.4) and 90 hours (3.3 ± 0.3) post-match and between 60 hours (3.3 ± 0.4) and 170 hours (3.5 ± 0.5) post-match (Figure 7.4).

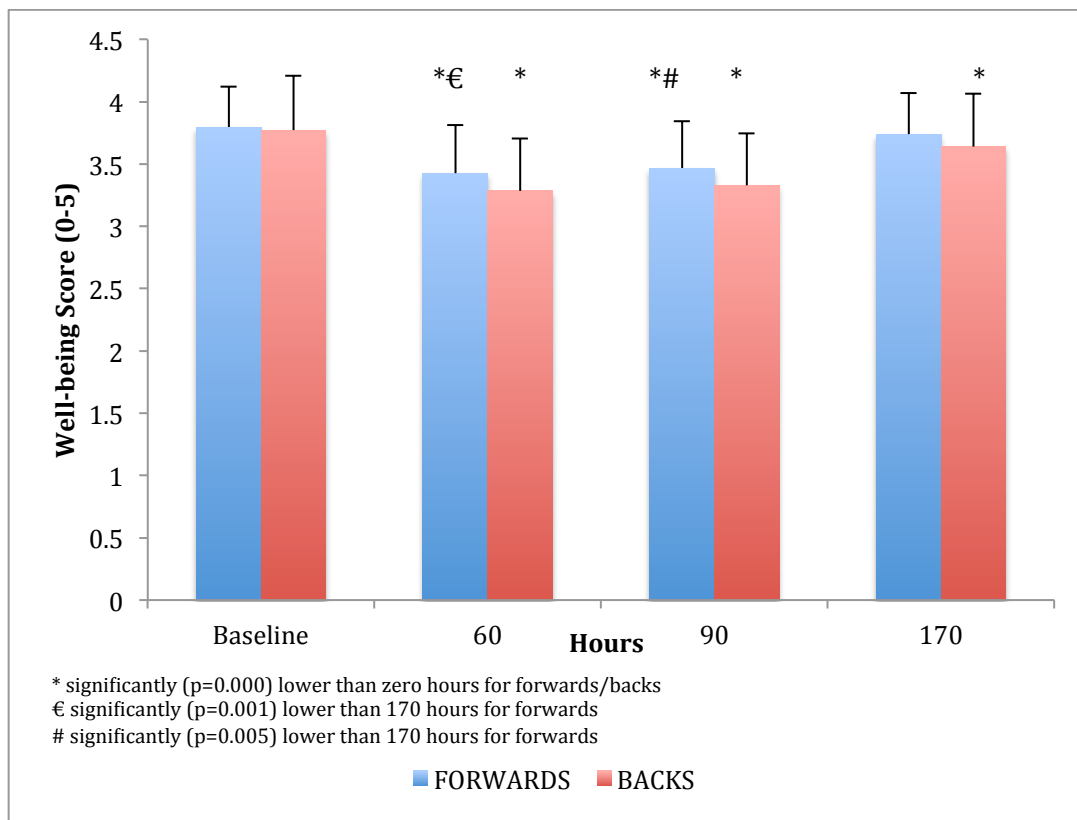


Figure 7.4: Changes in WB score pre to post-match (Forwards n=31; Backs n=28)

7.4.5 Relationships between match data and changes in CMJ performance and WB scores

Shapiro-Wilk tests of normality revealed that within the GPS variables, intensity and D5, were normally distributed ($p > 0.05$), yet total distance covered, D6, accelerations, decelerations, sprints, ImZ4, ImZ5 and ImZ6 were not normally distributed ($p < 0.05$). As a result, Spearman's correlations with Bonferonni post-hoc analysis were conducted showing no significant relationship between CMJ and WB and the match demands variables selected for analysis at 170 hours post-match. However, Spearman's correlations were strong and significant between total distances covered, decelerations, D5 and D6 at 60 hours post-match with changes in CMJ performance. Additionally, changes in CMJ performance displayed a strong and significant relationship between decelerations at 90 hours post-match (Table 7.2).

Table 7.2: Relationships between match data and changes in CMJ performance and WB scores

	Distance covered (m)	D5 (m)	D6 (m)	Decelerations	Im5	Im6
CMJ Change 60 hours	$r = 0.396$; $p = 0.016^*$	$r = 0.488$; $p < 0.001^*$	$r = 0.489$; $p < 0.001^*$	$r = 0.532$; $p < 0.001^*$	$r = 0.145$; $p = 2.716$	$r = 0.073$; $p = 4.656$
CMJ Change 90 hours	$r = 0.244$; $p = 0.496$	$r = 0.133$; $p = 2.520$	$r = 0.294$; $p = 0.192$	$r = 0.365$; $p = 0.032^*$	$r = -0.111$; $p = 3.224$	$r = -0.025$; $p = 6.800$
WB Change 60 hours	$r = 0.305$; $p = 0.152$	$r = 0.322$; $p = 0.104$	$r = 0.186$; $p = 1.264$	$r = 0.072$; $p = 4.712$	$r = 0.144$; $p = 2.216$	$r = 0.056$; $p = 5.400$
WB Change 90 hours	$r = 0.188$; $p = 1.232$	$r = 0.185$; $p = 1.288$	$r = 0.158$; $p = 1.832$	$r = -0.031$; $p = 6.544$	$r = -0.114$; $p = 3.128$	$r = -0.141$; $p = 2.296$
* statistically significant ($p < 0.05$)						

7.4.6 Relationships between match data and changes in CMJ performance and WB scores across positional groups

When assessing the relationships between match characteristics and both CMJ and WB (forwards $n = 31$; and backs $n = 28$), similarly to the whole sample group ($n = 59$), no significant relationships were noted for selected match demands variables at 170 hours post-match for both positional groups. However, Spearman's correlations with Bonferonni post-hoc analysis were conducted, showing a strong and significant relationship between accelerations at 60 hours post-match with changes in CMJ performance for the forwards only. No significant relationships were noted for selected match demands variables at 90 hours post-match for both positional groups (Table 7.3).

Table 7.3: Relationships between match data and changes in CMJ performance and WB scores across positional groups

	D6 (m)	Accelerations	Decelerations	Im6
Forwards CMJ Change 60 hours	$r = 0.364$; $p = 0.352$	$r = 0.558$; $p = 0.008^*$	$r = -0.177$; $p = 2.720$	$r = -0.023$; $p = 7.208$
Forwards CMJ Change 90 hours	$r = -0.036$; $p = 7.576$	$r = 0.365$; $p = 0.352$	$r = -0.373$; $p = 0.312$	$r = -0.260$; $p = 1.264$
Backs CMJ Change 60 hours	$r = 0.203$; $p = 2.408$	$r = 0.102$; $p = 4.840$	$r = -0.028$; $p = 7.104$	$r = 0.243$; $p = 1.696$
Backs CMJ Change 90 hours	$r = 0.209$; $p = 2.280$	$r = -0.255$; $p = 1.520$	$r = -0.130$; $p = 4.072$	$r = 0.026$; $p = 7.160$
Forwards WB Change 60 hours	$r = 0.162$; $p = 3.080$	$r = 0.248$; $p = 1.432$	$r = 0.158$; $p = 3.160$	$r = 0.115$; $p = 4.296$
Forwards WB Change 90 hours	$r = 0.045$; $p = 6.488$	$r = 0.206$; $p = 2.136$	$r = -0.008$; $p = 7.744$	$r = -0.119$; $p = 4.200$
Backs WB Change 60 hours	$r = 0.012$; $p = 7.600$	$r = -0.035$; $p = 6.872$	$r = 0.358$; $p = 0.496$	$r = 0.012$; $p = 7.608$
Backs WB Change 90 hours	$r = 0.083$; $p = 5.408$	$r = -0.238$; $p = 1.792$	$r = 0.196$; $p = 2.536$	$r = -0.188$; $p = 4.400$
* statistically significant ($p < 0.05$)				

7.5 Discussion

The main finding of this study supports previous research (McLean et al., 2010; McLellan et al., 2011b; Twist et al., 2017; West et al., 2014) and that which was hypothesised prior to testing, illustrating clearly that a delay of restoration of CMJ performance and reduced WB scores is present in the immediate days post rugby union match play. It is, however, important to note that some findings in this study are in contrast to those hypothesised. For example, it appears that backs experience greater reduction in both CMJ and WB post-match and take longer to recover post-match, in comparison to forwards. It was also of note that WB provided a more sensitive measure of time-course of restoration compared to that of CMJ.

7.5.1 Normal CMJ change

Across the whole sample group (forwards and backs), significant changes were observed for CMJ performance between baseline pre-match and all three time-points assessed post-match (60 hours, 90 hours and 170 hours post-match). No significant changes were, however, observed for CMJ performance between 60 and 90 hours post-match, yet they were noted between 90 hours and 170 hours post-match. The change in CMJ performance compared to baseline was shown to be -6.5% at 60 hours post-match, -7.0% at 90 hours post-match and -3.0% at 170 hours post-match, with individual variations identified upon inspection. Time-course of recovery assessed via CMJ performance has previously been identified in other studies, with at least two days modified activity post-match recommended to facilitate optimal recovery in rugby league (McLellan & Lovell, 2012). Many similar studies (Maso et al., 2004; Smart et al., 2008; Takarada, 2003) have used other testing indices (creatine kinase, testosterone and cortisol) to measure return to baseline post-matches of rugby union, with recommendations also being made for training in the 48 hours post-match.

In contrast to the results of this study, previous research assessing CMJ post fatiguing exercise has reported no decreases in CMJ output (jump height), although comparison with these results could be questioned as they did not involve rugby players (Boullosa, Tuimil, Alegre, Iglesias, & Lusquiños, 2011; Cormack, Newton, & McGuigan, 2008). The CMJ performance reduction, noted at 60 hours post-match within this study (-6%), was assumed to be a result of match exertion, which included blunt trauma (Average Im5 = 45; Im6 = 57) and the total distance (4692 m averaged across the games) covered by the players during a game. Perhaps most important for consideration, is the notion that the significant decrease ($p < 0.001$; 2.6 cm, -6.5%) in CMJ in performance at 60 hours post-match seen within this study, is greater than the measurement error previously reported 1.0 cm (-2.4%) in Chapter 6, when assessing CMJ reliability between sessions. One could, therefore, assume that a change of 2.6 cm (-6.5%) is meaningful and cannot be accounted for by measurement error. As a result, future research investigating CMJ performance post-match warrants altered training prescription in the immediate days post-match, in order to ensure a greater likelihood of improved restoration of performance. Further support for this -6% change being meaningful, is evidenced by previous researchers (Cormack et al., 2013; Cormack, Newton, & McGuigan, 2008; Cormack, Newton, McGuigan, & Cormie, 2008; Mooney et al., 2013), who noted that an -8% decrease in FT:CT was indicative of NMF. Of note, however, for practitioners when assessing prior research, is that, firstly, many of these studies were conducted in Australian rules football and secondly, that the reliability of FT:CT and the calculation used to equate these values has been questioned (Gathercole, Sporer, & Stellingwerff, 2015).

Twist et al. (2012) reported an inverse relationship between game contacts and impaired flight time during a CMJ, indicating that players that are involved in more contacts experience more loading on the lower limbs musculature. It could be argued that the decreased CMJ performance observed in this study could be attributed to several factors: muscle damage of the lower limb, possibly resulting from the number of contacts encountered during game play; neurological fatigue; or the large proportion of accelerations and decelerations performed prior to contact situations. McLellan et al. (2011b) found similar results with reductions in PRFD attributed to the trauma from contact situations and noted not to restore until 48 hours post-match. It is, however, important to note that biochemical markers in the hours post-match were noted to take longer to recover than PRFD, with CK remaining elevated up to 120 hours post-match. The effect of contacts experienced in games upon PRFD within jump testing, as

reported by McLellan and Lovell (2012), should perhaps be combined with findings from other performance measures to provide more detail within future time-course of recovery investigations.

Despite the results from this study illustrating the ability for CMJ height to detect changes in restoration of performance post-match, the results of the research by Gathercole, Sporer, Stellingwerff, et al. (2015a) are, however, important for consideration. In an analysis of male college-level team-sport athletes, Gathercole, Sporer, Stellingwerff, et al. (2015a) noted that most kinetic variables take longer to return towards baseline values at 72 hours post-exercise, when compared to CMJ output (typically concentric focused variables), with these views further supported in elite rugby union (Kennedy & Drake, 2017a; Kennedy & Drake, 2017b). Gathercole, Sporer, Stellingwerff, et al. (2015a), therefore, recommended that practitioners consider NMF by assessing changes in both output and/or movement economy. The main reasoning for the inclusion of kinetic data, when assessing fatigue by many authors, (Cormie et al., 2009; Ebben et al., 2007; Gathercole, Sporer, & Stellingwerff, 2015; Gathercole, Sporer, Stellingwerff, et al., 2015a; Gathercole, Stellingwerff, et al., 2015), is that the biphasic SSC-recovery pattern that exists following team-sport play, needs to be considered to gain a more thorough analysis of NMF response. Biphasic trends can be explained by the neural and mechanical responses resulting from muscle damage experienced during exercise. As muscle damage is commonplace within rugby union match play (Johnston, Gabbett, et al., 2014; Jones et al., 2014; McLellan & Lovell, 2012; Takarada, 2003; West et al., 2014), the influence of biphasic SSC-recovery pattern is a consideration that warrants attention by future researchers. Such views are further endorsed when considering the recent research in elite rugby (Kennedy & Drake, 2017a) showing kinetic values decreasing by a greater amount than outcome measures post rugby union training. However, despite kinetic values deemed more sensitive to fatigue, the aforementioned disadvantages of kinetic methods of assessment make this form of testing less viable for daily use in applied settings.

7.5.1.1 CMJ performance between positional groups

One surprising finding of this study is the lack of contrast between the CMJ performance of backs between 60 and 170 hours post-match. When considering that 170 hours post-match is immediately pre the following game, this would intimate that performance has not restored to optimal levels prior to commencement of the next game. Despite forwards not displaying any significant reductions in CMJ performance at three time-points post-match (-3.3% reduction in CMJ performance at 60 hours; -1.5% reduction in CMJ performance at 90 hours), these values are smaller than those noted for backs at 60 hours post-match (-9.6% 60 hours post-match; -9.5% 90 hours post-match). One could assume, therefore, that backs experienced more adverse effects than forwards in the immediate hours post-match. A smaller muscle damage response and the resultant effect upon positional CMJ change was reported in a study by Twist et al. (2012) assessing NMF (CMJ flight time; 24 hours Backs -2.9%, Forwards -3.9%; 48 hours Backs -2.3%, Forwards -1.2%). However, as this research by Twist et al. (2012) was taken from rugby league and assessed CMJ via a different method to that undertaken within this research, it should be considered with caution. More significant for this experimental study is research from professional rugby union, specifically the finding of Tee et al. (2016) that forwards suffer progressively greater performance decrements over the course of match play compared to backs. This notion would therefore perhaps indicate that forwards are likely to experience longer time-course of recovery as a result of the fatigue; yet the data presented in this chapter contradicts this.

The greater decrement in jump performance observed for backs, compared to forwards within this research, is supported by the finding that this decrement also lasted for longer amongst backs compared to forwards, as represented by the lack of restoration for backs at 170 hours post-match. When viewing these results specifically, it could be assumed that a greater and longer decrement in jump performance is representative of a higher level of fatigue, which has manifested itself into a longer time-course of recovery. Despite match characteristics within this study being normally distributed and this experimental study not being able to identify the exact mechanisms that caused this greater and longer decrement in backs, the differences observed in magnitude and length of decrement experienced by backs, compared to forwards, could perhaps be explained by the match demands encountered. This is also evident when considering the results from Chapter 3.4.1, which identified that backs completed significantly more game minutes, at greater intensity and with significantly more distance covered in D1, D4 and D6 than forwards. This identification of differences in match demands between positional groups, when considered alongside the magnitude and decrement of performance restoration reported within this study, is therefore of interest for future practice.

Another potential reason for the lack of restoration of CMJ performance amongst backs, noted within this study, is that the training sessions undertaken in the days post-match also influenced backs' restoration of recovery rates, thereby not allowing them to return to expected pre-game levels. Forwards, in contrast to backs, were deemed to be more capable of returning to optimal levels of performance post-match, with, surprisingly, no significant difference in CMJ performance at 60 hours post-match, despite training sessions between games being common. The research by Johnston et al. (2015), which shows more highly trained individuals (in terms of relative strength and aerobic capacity) recovering faster, is also of consideration when assessing the differences in rates of restoration between forwards and backs. Based upon the research by Johnston et al. (2015), this more rapid restoration of performance for forwards compared to backs, could perhaps be explained by forwards typically demonstrating higher levels of strength, although no conclusions can be made upon this notion as the supporting evidence to confirm these thoughts is lacking.

Despite match characteristics within this study being normally distributed, the finding that backs did not restore performance prior to the next game could also perhaps be explained by the cumulative fatigue experienced from training. Training completed by backs between games is different to that of forwards, with more emphasis being placed upon high speed running and high intensity effort such as accelerations and decelerations, and could, therefore, explain the inability of backs to restore performance between matches. Further evidence illustrating the influence of training upon decreased CMJ output, was presented by Gathercole, Sporer, and Stellingwerff (2015), with longitudinal NMF testing of rugby players using CMJ height recommended. The results from this study show that the differences in restoration rates for forwards and backs between games is one that warrants attention and is an area of future investigation for practitioners, where assessment of specific match characteristics is required.

7.5.2 Normal WB change

Across the whole sample group (forwards and backs), significant changes were observed for WB between baseline pre-game and all three time-points assessed post-match (60 hours, 90 hours and 170 hours post-match). No significant changes were, however, observed for WB between 60 and 90 hours post-match. The change in WB scores was shown to be -9.0% at 60 hours post-match, -9.8% at 90 hours post-match and -3.1% at 170 hours post-match, with individual variations identified upon inspection. Similar to results reported in research within

professional rugby league by McLean et al. (2010), this study showed that overall WB remained significantly reduced at 60 hours post-match. The magnitude of change in WB scores noted within this study was similar to that reported by Halson et al. (2003), where mood state alteration was seen during intensified training periods in overreaching cyclists (POMS-65 90.4 during normal training; 116.4 during intensified training period). Nicholls et al. (2009) noted that rugby union players reported many self-report stressors as being “worse than normal” the day after a match, in comparison to days preceding and including match day. Additionally, in a study involving Australian rules football players, Gastin, Meyer, and Robinson (2013) noted that subjective ratings of wellness appeared sensitive to changes in load, which support the finding from this study that despite WB values reducing in the immediate hours post-match, WB improves post-match as the next match day approaches. It is, however, important for practitioners to note that comparison of reduced WB scores to other research is difficult, as often figures reported are taken from arbitrary values and therefore cannot be judged against values from other research. Additionally, as WB questionnaire-scoring protocol varies, the ability to quantify a meaningful change is difficult. As a result practitioners are, therefore, advised to use % change values instead of absolute values. This notion is evidenced by the large individual variations in WB scores identified within this study and is supported in recent research by Roe et al. (2015), which presented a CV of 7.1% for WB questionnaires, which despite being lower than the recommended <10% CV noted by Buchheit et al. (2011) is a point of consideration for future research.

One could argue that the use of well-being questionnaires in team sport settings are especially important, considering that each individual might respond in a different manner, as a result of the training dose administered by the coaches. This notion of varied individual responses to training dose is supported by evidence presented in the study by Lovell et al. (2013), assessing factors affecting rate of perceived exertion (RPE) in rugby league. The categorical nature of questionnaire data means that a small change is difficult to detect, not only because WB scores change in increments of one but also because the reliability of such measures are difficult to quantify. It could, however, be concluded from this study that performance test data assessing neuromuscular function, combined with perceptual data from questionnaires, would provide a more accurate understanding of player fatigue, as the changes in CMJ performance and WB appear to represent a similar trend. As reported by Twist and Highton (2013), the multifaceted elements of fatigue and the physical and mental responses that individual athletes demonstrate, mean that single biochemical, hormonal or performance tests do not present a clear picture of athlete readiness. Instead athletes should be monitored within a multi-method approach that would assess any change below baseline. Recent research by Gathercole, Sporer, and Stellingwerff (2015), assessing the influence of increased training load upon elite female rugby players, noted a meaningful correlation ($r = 0.34$) between wellness and CMJ flight time, therefore supporting the use of WB data for assessing restoration of performance post rugby union match play.

7.5.2.1 WB scores between positional groups

Similarly, as reported for CMJ performance, backs displayed WB scores in the hours post-match that would signify that sub-optimal perceptions of WB were present immediately prior to subsequent matches, therefore indicating residual fatigue. Forwards displayed a -9.7% reduction in WB score at 60 hours, an -8.6% reduction at 90 hours post-match and a -1.4% reduction noted at 170 hours post-match. These values are smaller than the -12.9% reduction noted at 60 hours post-match, -11.8% reduction noted at 60 hours post-match and -3.5%

reduction noted at 170 hours post-match for backs. As was noted for CMJ performance, reductions in WB scores are longer lasting amongst backs than forwards, which could, perhaps, also be explained by the match demands encountered, or the typical, accumulated training activities performed between matches.

7.5.3 Performance reduction across 170 hours assessing both CMJ and WB

Despite previous research showing that restoration of performance is restored at 60 hours post rugby union match play (West et al., 2014), the results from this research are contrasting as both CMJ performance and WB scores are seen not to be restored back to pre-game levels at 170 hours post-match. The cumulative fatigue apparent in this research, as presented by reduced WB and CMJ values (throughout microcycles), is similar to the research of Cresswell and Eklund (2006), who assessed burnout across a playing season using questionnaires. A decrement in performance measures throughout a competitive playing period is perhaps no surprise, considering both the movement demands executed in each of the matches and the weekly competitive structure of professional rugby, where players are required to perform every weekend for a period of nine months. Similarly to this research, Alaphilippe et al. (2012) supported the view that fatigue (assessed by biochemical parameters) increased throughout a playing season in rugby union. Alaphilippe et al. (2012) investigated biochemical markers over the course of a playing season and noted correlations between overtraining scores and biochemical makers, while also noting a positive correlation between minutes played and increased CK levels. The evidence from this study would also indicate that cumulative fatigue across a playing season had an effect upon restoration of performance. It is, however, important to note that training within these days between matches may have had a larger influence upon performance measures than matches themselves, and could therefore have contributed to reduced CMJ and WB values at 170 hours post-match.

Lastly, it is important for practitioners to note that the previous research showing a decrement in performance lasting for less than 170 hours post-exercise (McLean et al., 2010; McLellan et al., 2011b) was not taken from rugby union. In addition, it should be noted that the data from much of the previously mentioned research assessing recovery post rugby union match play, is collected from the southern hemisphere (Coutts, Reaburn, Piva, & Murphy, 2007; Johnston et al., 2015; Johnston, Gabbett, et al., 2014; Lindsay, Lewis, Scarrott, Gill, et al., 2015; Maso et al., 2004; McLean et al., 2010; McLellan & Lovell, 2012; McLellan et al., 2011a, 2011b; Takarada, 2003). As noted by Gannon, Stokes, and Trewartha (2015), the structure of the playing and training season in the southern hemisphere is very different to that of the north, due to the reduced number of matches played in the southern hemisphere and the subsequent impact that this has upon windows of opportunity to train. In the southern hemisphere, the cumulative fatigue throughout a playing season could be argued to be less than that seen in the northern hemisphere, where players are often required to play more than thirty games per season (approximately one every week). This reduced match demand, would therefore likely manifest itself in an increased ability of rugby union players in the southern hemisphere to restore performance post-match more quickly.

7.5.4 Relevance of GPS parameters upon CMJ performance and WB scores

Within this study, significant relationships were noted between selected GPS parameters and CMJ performance only. It was noted that as distance covered increased, percentage change in CMJ performance worsens ($p < 0.05$), implying that the distance covered by players during games had an effect upon resultant CMJ performance at 60 hours post-match. Time spent in D5 and D6 also presented a significant relationship with CMJ performance ($p < 0.05$) at 60 hours

post-match, meaning that practitioners could assume that a greater time spent in D6 would lead to a greater reduction in restoration of performance post-match play. From the results of this chapter, it was also interesting to note that decelerations (many of which are likely to be completed post D6 movements) were significantly correlated with CMJ performance at 90 hours post-match ($p < 0.05$). This view that a greater number of decelerations and time spent in the higher speed zones (D5 and D6) are correlated with reduced CMJ performance, would be of significant interest to practitioners when assessing outside backs' restoration of performance. When considering the large volume of the high intensity metrics (accelerations, decelerations and sprints) that backs complete within match play (as illustrated within Chapter 3), the role that this might have upon time-course of restoration of performance is further emphasised.

Prior research (Quarrie et al., 2013) recommends that practitioners provide forwards with more time to recover post-match than backs, given the greater contact loads they sustain, yet evidence from this study would dispute these views, when considering its results that show longer time-course of recovery associated with backs, compared to forwards. Despite strong correlations existing between forwards' accelerations tasks and reduced CMJ performance (Table 7.3), no significant difference existed for CMJ performance at any time-point post-match. This point would therefore dispute the view that collision and contact situations were responsible for reduced CMJ performance, as, in contrast to backs, no correlations were observed between impacts and CMJ performance and no reduction in CMJ performance is noted amongst forwards at any time-point post-match. The larger number of Impacts > Zone 3 (noted within Chapter 3) attributed to forwards, perhaps suggests that forwards experience a large volume of blunt trauma during match play. Evidence from this chapter would, however, suggest that this trauma is not a factor in CMJ performance scores post-match. Instead, perhaps, the trauma that forwards experience is mainly upper body trauma associated with their positional tasks and therefore the resultant NMF that experienced affects the upper and not the lower body. Similarly, since CMJ measures lower body power via movement of the lower limbs, trauma to the lower body would be more likely to affect its performance than upper body. Upper body trauma is just as likely to occur during match play, yet the influence this has upon CMJ performance is questionable and should, therefore, be assessed via a more specific testing protocol.

7.5.4.1 Relevance of GPS parameters upon CMJ performance and WB scores between positional groups

On further analysis of the relationships between match variables across both positional groups, it was interesting to note that a significant relationship ($p < 0.05$) was noted between CMJ and accelerations at 60 hours post-match. It could, therefore, be argued that the existence within forwards, of this relationship between greater frequencies of accelerations at 60 hours post-match and reduced CMJ performance is perhaps due to forwards having to accelerate and decelerate into contact situations during games. These greater number of contact situations experienced by forwards, compared to backs, which was reported in previous research (Jones et al., 2015; Jones et al., 2014) (Forwards 31 ± 14 ; Backs 16 ± 7), could result in the significant relationship shown between forwards' accelerations and CMJ performance in the days post-match. Despite backs completing more sprints and time spent in D6 during match play (as represented in Chapter 3), compared to forwards, the results from this chapter show that forwards perhaps experience a greater level of fatigue from acceleration tasks. Considering that many of forwards' accelerations are performed prior to contact/collision situations and

therefore result in a greater level of neuromuscular fatigue, as represented by reduced CMJ performance, the relationship identified is perhaps more clearly understood. Additionally, when considering that forwards typically play for fewer minutes than backs (Table 3.4; Chapter 3), and therefore undertake a more intensified period of work, and that this study provides evidence of the effects of these on restoration, then this should be a major area of consideration for practitioners.

As a result of the aforementioned identification, that forwards experienced more impacts than backs (Chapter 3), this was perhaps an area that would have been expected to show positive correlations with CMJ performance and WB scores. However, when assessing the playing group as a whole ($n = 59$) no correlations existed amongst Im5 and Im6. Further analysis of both positional groups (forwards $n = 31$; backs $n = 28$) also showed no significant relationship between impacts and CMJ performance or WB scores. The absence of a correlation between impacts and delayed restoration of performance is somewhat surprising, yet could perhaps be explained by the small sample size within this research, and therefore one that warrants further investigation. This finding could also perhaps be explained by the notions proposed by both Lindsay, Lewis, Scarrott, Draper, and Gieseg (2015) and Reardon et al. (2016) that the force, angle and body parts involved in collisions are likely to be a determining factor influencing muscle damage and therefore restoration of performance. Considering the significant relationship discovered regarding accelerations amongst forwards and reduced CMJ performance, along with the potential influence of accelerations into contact/collision situations, the need to assess where the high level impact actually occur within positional groups' match demands, is an area of potential future research. Improved ability of practitioners to quantify where high level impacts occur within the match and whether or not they involved accelerations, decelerations and/or contact situations within the same instance of play, will shed further light upon player match demands and their probable effect upon restoration of performance.

7.5.5 Limitations of the research

Along with the aforementioned need to increase the sample size within this research, the main limitation involves the lack of multiple time-points post-match, upon which to assess change in CMJ performance and WB scores. Additional time-points, prior and post the 60 hours post-match, would have provided added value to the research. The inability of the researcher to gain additional testing time-points was due to logistical constraints of the players training schedule in the days post-match, meaning that access to players for assessment was limited. This limited access to players in the days post-match is considered a "real world" scenario within elite team sport settings, where days off from training are often employed to enhance recovery and improve performance restoration.

Another possible limitation with this study is that, similarly to previous research (Cormack, Newton, McGuigan, & Cormie, 2008; McLean et al., 2010), analysis of CMJ performance was focused upon outcome related variables. As discussed previously (Chapter 5), the analysis of kinetic variables that assess the SSC (specifically eccentric components of jumping movement) would provide more detail on the reasons for lack of restoration of performance. Despite the focus of this study being to detect time-course of recovery of CMJ and WB measures and not to detect NMF, it is perhaps also a limitation of the study, that no inclusion of kinetic values was made after considering the evidence presented by Gathercole, Sporer, and Stellingwerff (2015). Assessment of NMF and assessment of time-course of recovery are two distinct processes and should warrant separate testing protocols, although it should be noted that the link between

the two areas of focus could provide future direction for research practices. Lastly, despite biochemical analysis being an expensive and inconclusive performance measure (as outlined in chapter 2.4.4), its use in future investigation is warranted in order to gain a better understanding of the physiological cost of games and perhaps help advise practitioners upon which activities to undertake in the days post-match. This lack of inclusion of physiological analysis of the performance decrement observed could therefore also be considered to be a limitation of this study.

7.6 Practical implications

The findings of this study indicate that both CMJ performance and WB were reduced at 60 hours post-match, 90 hours post-match and 170 hours post-match, with changes reported similar to previous research (Cormack, Newton, McGuigan, & Cormie, 2008; Cormack, Newton, McGuigan, & Doyle, 2008; Gastin, Meyer, et al., 2013). Restoration of performance improved from 60 hours to 170 hours post-match, yet was still noted to be below pre-game levels at this later time-point. When considering results from Chapter 4, showing meaningful change in CMJ between-sessions [1.0 cm (2.4%)], practitioners should, perhaps, keep in mind the magnitude of the CMJ decrement before adjusting individual player training prescription. Also, when making decisions upon individual player training prescription, practitioners are advised to consider the positional group, as data from this study shows that forwards tend to restore performance at a quicker rate than backs.

This research also shows that WB is reduced to a greater value and for a longer time-course than CMJ between baseline and 60 hours post-match (CMJ -6.5%; WB -9.0%), baseline and 90 hours post-match (CMJ -7.0%; WB -9.8%) and baseline and 170 hours post-match (CMJ -3.0%; WB -3.1%). Consideration for these values and differences in time-course of recovery between CMJ performance and WB scores should be noted by practitioners when implementing training schedules in the days post-match. This support for the use of WB questionnaires is an important finding from this study, as many rugby clubs with limited resources, could implement its use, as, not only is it cost effective, but results from this study show that it is also a good indicator of performance change. Despite insufficient recovery, prior to commencing another training session or game, being common in many team sport environments, as well as being an important aspect that should be considered when preparing athletes, this in not one that should cause much concern. The more important concern should perhaps be the level of performance decrement although not simply that there is a decrement in the first place. Implementing performance testing into daily training schedules is perhaps the most difficult aspect for many practitioners in the field; yet this research adds support to the use of CMJ and WB to measure restoration of performance. When considering that players are required to resume resistance training in the immediate days following a match, gym-based sessions could perhaps provide the opportunity for coaches to monitor performance during exercises such as CMJ, upon which they could make decisions on readiness to train. If practitioners are confident in making informed decisions based upon readiness of their athletes to perform, improved performance and reduced incidence of injury from training and competition are seemingly to occur. In addition to practitioners being able to make informed decisions upon whether athletes should train, perhaps the area that elite practitioners should be focusing upon should be the need to improve readiness if and when required and how to do so. Specific recovery protocols and adjustable training schedules in the day post-match are therefore of great importance.

7.7 Implications of experimental chapter 7 for subsequent studies

Results from this chapter support the use of both CMJ and WB to assess time-course of restoration in the days post match. However, the findings showing no significant correlations between CMJ height and high magnitude GPS impacts were surprising. A need therefore exists to assess the occurrence of GPS impacts during match play, via use of video recordings alongside GPS data. As the influence of high magnitude GPS impacts was noted as not being related to delayed time-course of restoration in the days post match, future research in this thesis needs to assess when and how often high magnitude impacts occur during match play and what activities players are performing when they accrue them.

8 Quantification of GPS impacts using video analysis in Elite Level Rugby Union

8.1 Abstract

An understanding of the impacts experienced by elite rugby players during match play, is an important consideration for practitioners in improving their ability to assess the influence these impacts may have upon restoration of performance post match play. The purpose of this study was to quantify the frequency and magnitude of impacts experienced during game, with specific attention paid towards those activities which resulted in impacts during game play, combining both GPS software and video analysis tools. This combination of methods enabled comparison between impact instances identified by the GPS, which could then be cross-referenced against video files to ascertain which match demands illicit these impacts. Using video analysis, data was collected upon nine participants (age 27.7 ± 5.5 years, height 186.1 ± 10.3 cm, mass 97.4 ± 13.2 kg, training age 9.4 ± 5.7 years), with results showing no significant difference in percentage distribution or absolute values of impacts resulting from decelerations ($p > 0.05$). RMANOVA revealed no significant difference in percentage distribution ($p = 0.028$) and absolute values ($p = 0.061$) for collisions occurring between impact zones. Friedman tests revealed a significant difference ($p < 0.001$) in the percentage distribution and absolute values of impacts as a result of changes of direction, with the greatest number of impacts from change of direction occurring in Zone 4 ($90.7 \pm 18.8\%$; 3.8 ± 3.2), which was significantly greater than the number of impacts from changes of direction in Zone 5 ($p = 0.015$, 0.0 ± 0.0 ; $d = 6.82$; $p = 0.007$, $0.0 \pm 0.0\%$; $d = 1.67$) and Zone 6 ($p = 0.021$, $9.2 \pm 18.8\%$; Cohen's $d = 4.33$; $p = 0.011$, 0.2 ± 0.4 ; $d = 1.57$). A significant difference ($p = 0.007$) in the percentage distribution of impacts as a result of accelerations was noted, however, results from Wilcoxon tests with Bonferroni correction revealed that no differences were observed between impact zones from accelerations. When assessing absolute values, Friedman tests revealed a significant difference ($p < 0.05$) in the frequency of impacts as a result of accelerations, with Wilcoxon revealing that the greatest number of impacts from accelerations occurred in Zone 4 (10.8 ± 13.2), which was significantly greater than the number of impacts from accelerations in Zone 5 ($p = 0.018$, 0.7 ± 1.3 ; $d = 1.07$) and Zone 6 ($p = 0.049$, 1.5 ± 2.2 ; $d = 0.98$). As was hypothesised, collisions accounted for higher magnitude impacts than other movements. As a result of this research, it can be concluded that player movement patterns identified from GPS impacts may provide misleading information. Practitioners working in the elite field are therefore recommended to combine video and GPS data to develop a greater representation of the match involvements assigned to impacts experienced during match play, as the values presented from GPS outputs alone cannot be taken at face value.

8.2 Introduction

The ability to identify and understand the specific match demands placed upon rugby players, has long been recognised as an essential component for developing appropriate training and recovery programmes, with the aim of improving subsequent performance (Roberts et al., 2008). The development of GPS and video analysis technology, provides sports science practitioners with detailed objective data relating to specific movement demands of players in rugby union (Austin & Kelly, 2013; Cummins et al., 2013; McNamara, Gabbett, Naughton, Farhart, & Chapman, 2013), with variations in match demands between position (Chapter 3)

(Cahill et al., 2013; Lindsay, Draper, et al., 2015; Reardon et al., 2017) and between playing levels (Cahill et al., 2013; Coughlan et al., 2011; Cunningham et al., 2016; Venter et al., 2011) also having been identified as being important. Many studies have attempted to assess the influence of match variables upon restoration of performance (Cunniffe et al., 2010; Duffield et al., 2012; Johnston et al., 2015; Johnston, Gabbett, et al., 2014; McLellan & Lovell, 2012), yet few studies have incorporated collision or impact variables when evaluating match demands.

Research by McLellan and Lovell (2012) noted that neuromuscular fatigue was highly dependent upon the number of heavy impacts (> 7.1 G) experienced during game play, with many authors noting positional differences in the number of impacts experienced during match play (Coughlan et al., 2011; Cunniffe et al., 2009; Lindsay, Draper, et al., 2015; Venter et al., 2011). Despite the research by McLellan and Lovell (2012) involving both time-motion analysis and GPS in assessing the influence of neuromuscular impacts and collisions during elite rugby league match play, the results presented did not quantify which specific match movements exhibit muscle trauma that would delay post-match restoration of performance. The need for a more detailed analysis of impacts resulting from accelerations, decelerations, changes of direction and collisions is therefore required, with an improved understanding of the impacts resulting from these match demands likely to benefit practitioners working in the elite field.

Both GPS and video analysis are regularly used in applied settings, yet both methods of data collection have limitations and benefits in their use. Time-motion analysis using video based analysis systems have been employed for the last 30 years to assess match demands (Deutsch et al., 2007; Duthie et al., 2003a) and continue to be utilised extensively in a variety of team sports (Di Salvo, Collins, McNeill, & Cardinale, 2006; King, Jenkins, & Gabbett, 2009; Spencer et al., 2004), with video analysis appearing to produce valid data (Duthie, Pyne, & Hooper, 2003b). Limitations of video analysis for assessing match demands do, however, exist, mainly in that it is a labour intensive process where, unlike GPS, only one subject can be tracked at a time, when using time-motion methods via one operator. In addition, the intensity of each activity collected via video analysis cannot be quantified, making match demands more difficult to assess. The reliability of time-motion analysis within rugby union has previously been researched by Duthie et al. (2003b), who noted that the total time spent by individuals performing movements involving static exertions (that are likely to incur impacts) presents moderate to poor reliability (5.8-11.1% TEM). Lastly, perhaps the most influential limitation of video analysis for assessing match demands is user error and the somewhat subjective measures that are involved within this data collection process. Inter and intra-reliability of data collected in video analysis is of note, with what one user may categorise as a specific movement or match demand, potentially being different to that of another user, thereby producing contrasting results. Variances in the reliability data for intra-coder analysis were previously investigated by Deutsch et al. (2007), with a typical error of measurement reported of 4.3-13.6%.

Support for time-motion analysis methods was noted by Dogramaci, Watsford, and Murphy (2011), with recommendations for the use of subjective notational analysis as being both valid and reliable in tracking player movements. Dogramaci et al. (2011) also recommended the use of notational time-motion analysis in place of GPS, when assessing field sports where short sprints and changes of direction are common, as a preferred and more effective method for movement analysis. However, the inability of video analysis to quantify magnitude of effort or impact within the events identified, means its use is limited. When considering that recent

technological advances in GPS solutions have provided practitioners with the ability to analyse data in real time with regards to players' movement intensity and resultant fatigue, time-motion analysis has become secondary within many team sport settings. Instead it is mainly used for post-match analysis by sport specific coaches, where decision-making and individual play within the context of the game are better displayed by time-motion methods. Reliability of GPS analysis in team sport settings has been confirmed in many previous studies (Coutts & Duffield, 2010; Cummins et al., 2013; Johnston, Watsford, et al., 2014; Varley et al., 2012), with Coutts and Duffield (2010) reporting total distance being stable between match variations in rugby league (< 5% CI), while Johnston, Watsford, et al. (2014) showed a larger degree of between match variability for higher speed activities (TEM = 0.8-19.9%). Critical movements for good performance in rugby include the ability to maximally accelerate, decelerate and change direction at speed over a short distance, yet when assessing the reliability and validity of team sport specific running patterns, Jennings, Cormack, Coutts, Boyd, and Aughey (2010) have questioned the use of GPS systems for the assessment of brief high speed straight line running (CV = 77.2%).

It is, however, interesting to note, that collision events recorded using GPS have been compared to video analysis and were noted to strongly correlate ($r = 0.89, 0.97$ and 0.99) with mild, moderate and heavy collisions respectively, therefore supporting GPS use (Gabbett, Jenkins, & Abernethy, 2010). In contrast, recent research in elite level rugby union (Reardon et al., 2016) illustrated inaccuracies in collision assessment, where the smallest mean difference between micro technology and video coding was noted at the 2.5 G collision threshold, with statistical differences noted between some positional groups. Further inaccuracies have been noted in elite level rugby union (Clarke, Anson, & Pyne, 2017; Kelly, Coughlan, Green, & Caulfield, 2012), where collision recall assessment (the ability to detect collisions with a low number of false positives) was noted as both gender (Women's = 0.45; Men's = 0.69) and code specific, between the fifteens (0.93) and sevens (0.45-0.73) versions of the game. The finding by Reardon et al. (2016) therefore has implications for future collision assessment, with the manipulation of G-force thresholds having no effect upon accuracy and the implementation of collision counts based upon a position-specific basis being recommended.

Impacts with opposition players or the playing surface in rugby union are also likely to induce muscle trauma and resultant fatigue, yet the commonly reported GPS and video analysis data collection limitations discussed above, mean that many of the movements that illicit and quantify impacts may be excluded from post-match analysis. A greater understanding of the highly specific game related activities involved within rugby union match play and the likely GPS impact associated with each movement is needed to better understand impacts incurred during specific match demands. An illustration of the response which impacts are likely to have upon post-match fatigue, was illustrated by Johnston, Gabbett, et al. (2014) where markers of muscle damage (CK blood analysis) following small sided rugby league games were reported to still be rising 24 hours following the contact game in comparison to the non-contact small sided game (ES 0.86). This view was also recently supported by Roe et al. (2017), who noted increased likelihood of upper body NMF, reduced well being and greater elevations in CK post training sessions involving contact than sessions without contact. As reported within rugby union time-motion analysis research (Deutsch et al., 2007; Docherty et al., 1988), the majority of collision events happen during tackle situations, potentially emphasising that a greater number of tackles has greater impact upon NMF. However, when considering that time-motion analysis only provides a frequency of events with no magnitude of load, some of the data

produced by time-motion analysis research may be erroneous and therefore misleading, meaning the implementation of GPS analysis to assess magnitude of load and subsequent influence upon restoration of performance is paramount as it provides the detail surrounding the impacts.

Reardon et al. (2016) stated that GPS technology was, however, not a valid technology for detecting rugby union collisions. A process of combined data collection including both GPS data and video recordings was recommended by Cunniffe et al. (2009) for use in elite rugby union in order to produce a more thorough analysis of match demands. In a study assessing playing demands in rugby by Cunniffe et al. (2009), more accurate data was collated via a triangulation of analysis practices. Cunniffe et al. (2009, p. 1202) stated that a “combination of GPS software with game recordings may produce more insight into categorisation of forces/accelerations received/exerted during the many contact elements within the game”. Despite recent research (Reardon et al., 2016) assessing collision counts in elite level rugby union existing, this experimental study differs as it aims to match single collision events coded by GPS to the relevant passage of play within the video file. The results of this study therefore have implications, not only for the players involved, but also for practitioners aiming to implement training sessions in the days post-match. Not only will the physical demand (created by impacts) placed upon the player within match situations be available, but also a video story of movement patterns (involving impacts) will be available for analysis. From the data produced, practitioners will be able to place accurate training expectations upon players in the days post-match, as the impacts experienced and the consequences of impacts upon player readiness can be analysed more fully.

The aim of this study was to identify which activities, based upon video analysis, are responsible for impacts at different intensities, with the intensity measured via the accelerometer in the GPS unit. Based upon results from previous chapters, impacts involving ≥ 9 G were identified as the most likely to impair subsequent performance and these therefore warranted further investigation. It was hypothesised, that as the impact increases, the percentage of impacts from collisions would also increase and the percentage of impacts from accelerations, decelerations and changes of direction would decrease. Findings from this study will provide further information upon the activities which result in the highest impacts experienced during match play. Evidence presented will therefore help practitioners to make more informed decisions upon future training prescription post rugby union match play, in order to increase the likelihood of subsequent optimal performance.

8.3 Method

8.3.1 Participants

The assessment period covered seven games during a competitive rugby union playing season, with data collected upon one individual from each of the nine positional groups including props (n=1), hookers (n=1), locks (n=1), back rows (n=1), scrum half (n=1), out half (n=1), centres (n=1), wings (n=1) and full backs (n=1); meaning nine sets of game data were assessed (age 27.7 ± 5.5 years, height 186.1 ± 10.3 cm, mass 97.4 ± 13.2 kg, training age 9.4 ± 5.7 years). This study was conducted in accordance with the Declaration of Helsinki and was approved by Salford University Institutional Review Board. All participants provided written informed consent to participate in this study.

8.3.2 Experimental approach

Both GPS and video analysis data provide information upon the impacts experienced during game play. Data was collected from the same rugby club for all nine positional groups, and if the player who started the game in one position was substituted, the data produced by the substitute player was combined with that of the original player, therefore providing a full game duration of the position being analysed. The GPS file used for analysis was a raw numerical data file, detailing where impacts occurred within the match day timeline. This GPS file was exported directly from the 10 Hz GPS units (*StatSports Viper*, Northern Ireland) detailed below in Chapter 8.3.3 and was subsequently imported into the video footage to ascertain whereabouts within the game these impacts occurred. Video footage was viewed throughout the duration of each game and a sense check was made with the *StatSports* data export to assess exactly what the impacts related to within the video file and whether this involved collisions, change of direction, accelerations or decelerations.

Collisions (including or excluding set piece elements of rugby union match play) across all positional groups was not considered a concern as the data comparison between all nine positional groups was normalised via percentage calculations of each collision occurring, meaning this potential disparity between positions was accounted for. In order to ascertain the match involvements and the impact associated with these movements, the GPS data provided the magnitude of the impact experienced by the players (illustrated by GPS impacts), while the video footage acted as a reference file against which to compare the GPS impacts. It is important for readers to note that this research used video analysis to view match involvements alongside the GPS data and did not employ typical time-motion analysis practices to assess movement patterns, thus providing speeds, distances and speeds of locomotive tasks as outlined by Dobson and Keogh (2007). As explained above, GPS use for locomotive tasks is considered superior to time-motion methods, therefore this research only used video analysis to clarify match involvements and not to quantify and compare locomotion against the GPS data.

8.3.3 Match analysis

8.3.3.1 GPS analysis

The match characteristics exported from GPS units included: accelerations, decelerations, collisions, sprints, impacts in Zone 4 (9-11 G), impacts in Zone 5 (11-13 G) and impacts in Zone 6 (> 13 G). Measurements were taken with 10 Hz GPS units (*StatSports Viper*, Northern Ireland) throughout all games in order to assess movement patterns. Player positions were defined as: (1) backs or forwards; (2) props, hookers, locks, back rows, scrum half, out half, centres, wings and full backs. The main focus of the GPS analysis was the assessment of impacts, using *StatSports Viper* GPS units, with the 100 Hz tri axial accelerometer being used to collate impacts and not GPS data. The GPS device measures GPS impacts when values are above 2 G in a 0.1 second period. Impacts are instantaneous moments throughout a match situation measured in G-forces and are expressed as a quantity, with a number of impacts at each of the 6 zones categorised in the *Viper* system. It is important to note that GPS impacts are a combination of collisions and impacts created from movement (stepping, jumping, and decelerations). For the purposes of discussing the impact zones, shorthand abbreviations were used. Impact zones were abbreviated to Im1 relating to impacts in Zone 1, Im2 for impacts encountered in Zone 2, Im3 for impacts encountered in Zone 3, Im4 for impacts encountered in Zone 4, Im5 for impacts encountered in Zone 5 and Im6 for impacts encountered in Zone 6 (Table 8.1). Accelerations and decelerations were also collated by the *StatSports Viper* GPS

unit, with this data collected purely by the accelerometer. Acceleration is a change in velocity/time (using GPS data), with individual acceleration thresholds similar across positional groups, based upon longitudinal analysis of players performing maximal accelerations. Prescribed zones were then categorised from these maximal values and manually inputted into the *StatSports Viper* software.

Table 8.1: Categorisation of impact zones

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Impacts in Zones (G)	3 - 5	5 - 7	7 - 9	9 - 11	11 - 13	13 - 15

8.3.3.2 Video analysis

Nine individual player videos were collected with all video recordings filmed on a digital camera (*Sony AX1 4K*) mounted on a tripod and captured via firewire onto an *Apple MacBook Pro* using *SportsCode* (version 10.3) analysis software. *SportsCode* software allowed the importing of the GPS data collected for further analysis via an xml edit list. The sole use of typical game footage (side on and covering multiple players) was considered too broad for use within this study as detailed analysis of an individual was the goal, therefore close up “side on” individual player cameras were also administered alongside. Regular rugby footage as seen on public television would show the individual playing within the team pattern, but would not provide specific detail surrounding the participant being analysed. As a result, the main television recording covering typical match footage was synchronised with the individual player video within *SportsCode*, to show the broader aspect of the game the individual is playing within, while also covering the detail of the individual required. For example, this combination of videos would supply greater detail to activities in contact situations, where typical television footage of the player may be obscured by other players on the field, or by replays of previously completed match events (scrum, ruck and tackle situations). Due to the nature of this study, parameters measured within both methods of assessment could be cross-referenced and validated against each other, as the timings were identical for both the GPS analysis and the video footage. As a result, from the video footage, practitioners would be able to determine if the impact data elicited by the GPS data at the moment in question is actually what is expected for these actions.

8.3.4 Statistical analyses

Statistical analysis was performed using SPSS Version 20 (IBM), with an *a priori* alpha level set at $p < 0.05$. Normality testing was conducted on both the percentages distribution of match characteristics and the absolute values that account for impacts occurring (changes of direction, acceleration, deceleration and collisions). Normality testing on percentages distribution and absolute values of match characteristics was conducted across impact Zones 4, 5 and 6 and comparisons between zones and positions were made. As playing positions are different in the match demands required (as illustrated in Chapter 3), analysis of the percentages distribution of match characteristics was considered important alongside analysis of absolute values. Repeated measures ANOVAs with Bonferroni post-hoc analysis, or non-parametric equivalent (Freidman test, with multiple Wilcoxon tests for pairwise comparison and subsequent Bonferonni correction applied) were conducted to compare the difference between percentage distribution of impacts incurred by collisions and those that resulted from changes of direction, acceleration or deceleration, across impact zones. Subsequent repeated measures ANOVAs with Bonferroni post-hoc analysis, or non-parametric equivalent (Freidman

test, with multiple Wilcoxon tests for pairwise comparison and subsequent Bonferonni correction applied) were performed to determine if there was a significance difference in the percentage of activities resulting in impacts within each zone. Furthermore, Cohen's *d* effect sizes (ES) were calculated to determine if any meaningful differences occurred, interpreted based upon the criteria suggested by Rhea (2004) and were interpreted as follows; trivial < 0.25, small = 0.25 - 0.5, moderate = 0.50 - 1.0 and large > 1.0.

8.4 Results

Shapiro-Wilks tests showed that data was normally distributed ($p > 0.05$) for the percentage distribution of Zone 4 collisions and decelerations, yet was not normally distributed for change of direction and accelerations. Additionally, the Shapiro-Wilks tests showed that data was normally distributed ($p > 0.05$) for the percentage distribution of Zone 5 collisions and decelerations, yet changes of direction and accelerations were not normally distributed ($p < 0.05$). Lastly, Shapiro-Wilks test showed that data was only normally distributed ($p > 0.05$) for the percentage distribution of Zone 6 collisions, while changes of direction, decelerations and accelerations were not normally distributed ($p < 0.05$). When assessing absolute values, the Shapiro-Wilks test showed that data was normally distributed ($p > 0.05$) for Zone 4 decelerations, yet not for change of direction, accelerations and collisions. Additionally, the Shapiro-Wilks test showed that data was normally distributed ($p > 0.05$) for the absolute values of Zone 5 decelerations, yet changes of direction, accelerations and collisions were not normally distributed ($p < 0.05$). Lastly, the Shapiro-Wilks test showed that data was normally distributed ($p > 0.05$) only for the percentage distribution of Zone 6 collisions, while changes of direction, decelerations and accelerations were not normally distributed ($p < 0.05$).

Figure 8.1 shows the frequency of impacts in Zones 4, 5 and 6 for each activity. When assessing these absolute values, RMANOVA revealed no significant difference ($p = 0.061$; Zone 4 = 15 ± 0.7 ; Zone 5 = 11 ± 0.6 ; Zone 6 = 13 ± 0.6) in collisions between impact zones (Figure 8.1). Friedman tests revealed that a significant difference ($p < 0.001$) occurred in the frequency of impacts as a result of changes of direction, with Wilcoxon revealing that the greatest number of impacts from change of direction occurred in Zone 4 (3.8 ± 3.2), which was significantly greater than the number of impact from changes of direction in Zone 5 ($p = 0.007$, 0.0 ± 0.0 ; $d = 1.67$) and Zone 6 ($p = 0.011$, 0.2 ± 0.4 ; $d = 1.57$). No differences were observed between absolute values for impacts from changes of direction between Zones 5 and 6 ($p > 0.05$). Friedman tests revealed that a significant difference ($p < 0.05$) occurred in the frequency of impacts as a result of accelerations, with Wilcoxon revealing that the greatest number of impacts from accelerations occurred in Zone 4 (10.8 ± 13.2), which was significantly greater than the number of impact from accelerations in Zone 5 ($p = 0.018$, 0.7 ± 1.3 ; $d = 1.07$) and Zone 6 ($p = 0.049$, 1.5 ± 2.2 ; $d = 0.98$). No differences were observed between impacts from accelerations between Zones 5 and 6 ($p > 0.05$). Friedman tests also revealed that no significant difference ($p > 0.05$) occurred in the absolute values of impacts incurred as a result of decelerations (Zone 4 = 12.6 ± 7.6 ; Zone 5 = 4.6 ± 2.6 ; Zone 6 = 1.1 ± 0.4).

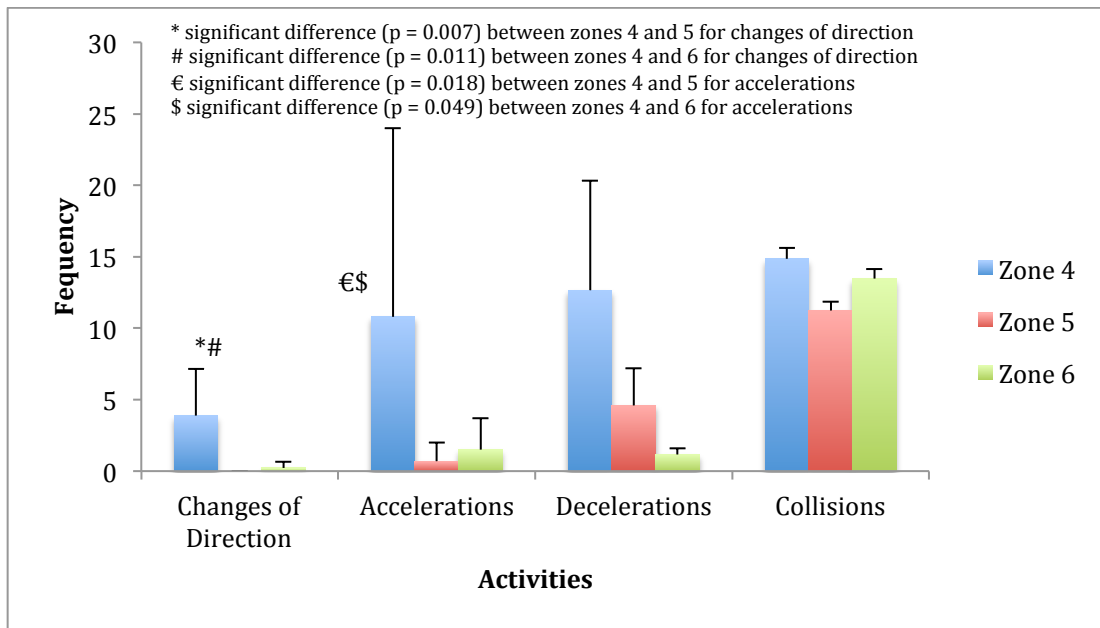


Figure 8.1: Frequency of impacts in Zones 4, 5 and 6 for each activity

Figure 8.2 shows the percentage of impacts in Zones 4, 5 and 6 for each activity. RMANOVA revealed no significant difference in percentage distribution ($p > 0.05$; Zone 4 = $38.0 \pm 40.0\%$; Zone 5 = $28.0 \pm 8.4\%$; Zone 6 = $34.0 \pm 32.1\%$) between impact zones from collisions (Figure 8.2). Friedman tests did, however, reveal that a significant difference ($p < 0.001$) occurred in the percentage distribution of impacts as a result of changes of direction, with Wilcoxon's tests highlighting that the greatest number of impacts from change of direction occurred in Zone 4 ($90.7 \pm 18.8\%$), which was significantly greater than the number of impacts from changes of direction in Zone 5 ($p = 0.015$, $0.0 \pm 0.0\%$; $d = 6.82$) and Zone 6 ($p = 0.021$, $9.3 \pm 18.8\%$; $d = 4.33$). No differences were observed between percentage distribution of impacts from changes of direction between Zones 5 and 6 ($p > 0.05$).

Friedman tests also revealed a significant difference ($p = 0.007$) in the percentage distribution of impacts as a result of accelerations, however, Wilcoxon's tests with Bonferonni correction revealed that no differences were observed between impacts from accelerations, between any of the impact zones (Zone 4 = $69.6 \pm 34.3\%$; Zone 5 = $8.6 \pm 12.3\%$; Zone 6 = $21.8 \pm 31.7\%$). In contrast to accelerations and changes of direction, Friedman tests revealed that no significant difference ($p > 0.05$) occurred in the percentage distribution of impacts as a result of decelerations (Zone 4 = $50.1 \pm 33.2\%$; Zone 5 = $19.2 \pm 16.9\%$; Zone 6 = $30.7 \pm 40.9\%$).

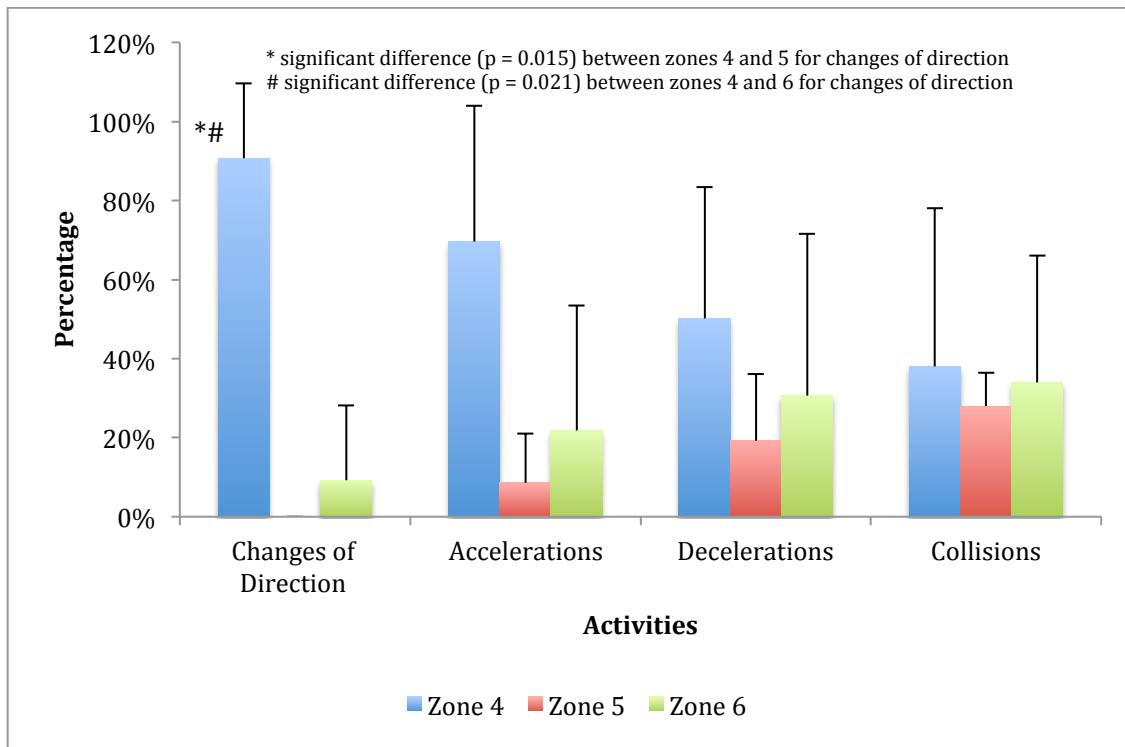


Figure 8.2: Percentage of impacts in Zones 4, 5 and 6 for each activity

Figure 8.3 shows the percentage distribution within and between zones for each activity, displaying that the largest frequency match demand in all zones was collisions (Zone 4 = $32.7 \pm 40.0\%$; Zone 5 = $61.9 \pm 8.4\%$; Zone 6 = $76.3 \pm 32.1\%$) and that the frequency of collisions increased in comparison to other zones as the magnitude of the impact also increased. Decelerations (Zone 4 = $27.9 \pm 33.2\%$; Zone 5 = $25.3 \pm 16.9\%$; Zone 6 = $6.6 \pm 40.9\%$) were noted to decrease as the magnitude of the impact increased, while accelerations (Zone 4 = $30.8 \pm 34.3\%$; Zone 5 = $12.8 \pm 12.3\%$; Zone 6 = $15.8 \pm 31.7\%$) and changes of direction (Zone 4 = $8.6 \pm 18.8\%$; Zone 5 = $0.0 \pm 0.0\%$; Zone 6 = $1.3 \pm 0.0\%$) were lowest in Zone 5. RMANOVA revealed that there were significant differences ($p < 0.05$) in the percentage distribution of impacts within Zone 4, Zone 5 and Zone 6. Friedman tests revealed that a significant difference ($p < 0.005$) occurred in the percentage distribution of impacts within Zone 4, with Wilcoxon's tests highlighting that the greatest number of impacts in Zone 4 occurred as a result of collisions ($32.7 \pm 18.8\%$), this being significantly greater than the number of impacts in Zone 4 from decelerations ($p = 0.012$, $27.9 \pm 33.2\%$) and changes of direction ($p = 0.008$, $8.6 \pm 18.8\%$; $d = 0.71$). No differences ($p > 0.05$) were observed between collisions and accelerations within Zone 4. Friedman tests also revealed a significant difference ($p < 0.005$) occurred in the percentage distribution of impacts within Zone 5, with Wilcoxon's tests highlighting that the greatest number of impacts in Zone 5 occurred as a result of collisions ($61.9 \pm 8.4\%$), this being significantly greater than the number of impacts in Zone 5 from changes of direction ($p = 0.012$, $0.0 \pm 0.0\%$) and accelerations ($p = 0.025$, $12.8 \pm 12.3\%$; $d = 1.47$). Lastly, Friedman tests also revealed a significant difference ($p < 0.005$) occurred in the percentage distribution of impacts within Zone 6, with Wilcoxon's tests highlighting that the greatest number of impacts in Zone 6 occurred as a result of collisions (76.3 ± 32.1), this being significantly greater than the number of impacts in Zone 6 from changes of direction ($p = 0.008$, $1.3 \pm 0.0\%$; $d = 3.30$).

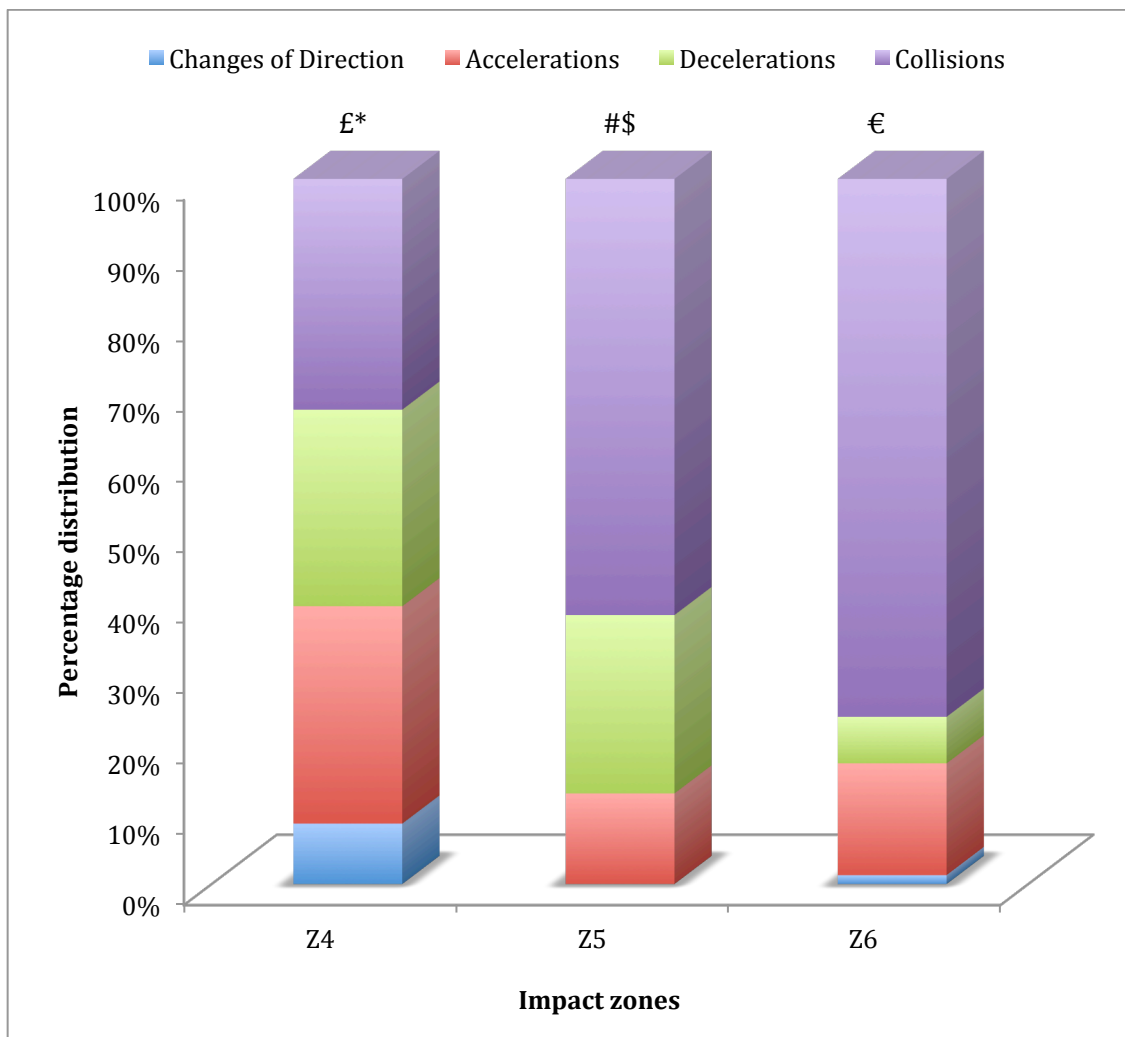


Figure 8.3: Percentage distribution of impacts across Zones 4, 5 and 6 for each activity

Table 8.2: Key of significant differences in percentage distribution of impacts across Zones 4, 5 and 6 for each activity relating to Figure 8.3

Key of significant differences

£ significant difference ($p = 0.012$) between collision and decelerations within Zone 4

* significant difference ($p = 0.008$) between collision and changes of direction within Zone 4

significant difference ($p = 0.012$) between collision and changes of direction within Zone 5

\$ significant difference ($p = 0.025$) between collision and accelerations within Zone 5

€ significant difference ($p = 0.008$) between collision and changes of direction within Zone 6

8.5 Discussion

The findings of this study indicate that the majority of the impacts registered during collisions are of a higher magnitude than accelerations, decelerations and changes of direction. In line with the hypothesis, the results confirm that as the magnitude of impacts increase the

percentage of impacts from collisions also increase and the percentage of impacts from accelerations, decelerations and changes of direction decrease.

8.5.1 Impacts resulting from collisions

When considering recent literature assessing the impacts encountered during rugby match play (Lindsay, Lewis, Scarrott, Draper, et al., 2015; McLellan & Lovell, 2012; McLellan et al., 2011a; Suarez-Arrones et al., 2014), one would assume that an impact of greater than 9 G (\geq Zone 4) would be a collision and the results from this experimental study further support this view. The notion that within Zone 6 the most impacts accrued were from collisions (Frequency = 13; Distribution = 76.3%) was expected within this study, yet the results from this study which showed a large contribution of impacts from collisions in Zone 4 (Frequency = 15; Distribution = 32.7%) was unexpected (Figure 8.1 and 8.3). The causes of the collision impacts occurring in Zone 6 are likely to be due to both the match demands occurring in open field play and those encountered within set piece elements of match play. Open field play collisions involve aggressive and forceful match movements in an attempt to avoid an attacking player gaining momentum, or in ruck situations where the opposition are attempting to regain possession of the ball. Similarly, set piece elements of match play involve close contact collision, whereby players are deliberately attacking weaknesses in the opposition's pre-planned set ups, with aggressive actions conducted to spoil possession and disrupt team momentum. When viewed during game play, collision actions are clearly very physical in nature and therefore unsurprisingly create the highest impact forces when compared to other match movements such as changes of direction, accelerations and decelerations. Players are required to exert maximal force onto the opposition during collision moments in an attempt to halt or continue momentum; meaning collision impacts occurring in Zone 6 are likely.

Much of the previous research in elite rugby union that has assessed impacts encountered during match play, has classified impacts as "heavy", "very heavy" or "severe", with impacts of these high magnitudes experienced during match play assumed to cause significant changes in markers of muscle damage (Coughlan et al., 2011; Cunniffe et al., 2009; Lindsay, Lewis, Scarrott, Draper, et al., 2015; McLellan & Lovell, 2012; McLellan et al., 2011a; Venter et al., 2011). Specifically, when assessing neuromuscular responses to impacts post rugby league match play, McLellan and Lovell (2012) noted "very heavy" and "severe" impacts were significantly correlated to change in PRFD and PP 24 hours post-match, with collisions that involved impacts > 8.1 G noted to result in prolonged neuromuscular fatigue. Additional research by McLellan et al. (2011a) in elite rugby league, noted that the number of impacts recorded in Zone 5 (8.1–10.0 G) and Zone 6 (> 10.1 G) during match play was significantly correlated ($p < 0.05$) to CK for up to 72 hours post-match and that the frequency of "heavy" to "severe" impacts experienced by players during match play also correlated with increased muscle damage for at least 72 hours post-match. More recent research (Lindsay, Lewis, Scarrott, Draper, et al., 2015) has noted positive correlations between total neopterin/specific gravity and total impacts ($p < 0.05$) following rugby union match play, further supporting the influence impacts have upon restoration of performance. Post-match muscle damage and the associated muscle catabolism are therefore of importance for consideration in the hours post-match, as performance decrements and delayed restoration of performance are likely.

8.5.2 Impacts resulting from changes of direction, accelerations and decelerations

As would be expected within this study, the largest number of changes of direction, accelerations and decelerations were accrued in Zone 4, yet surprisingly, only changes of direction revealed a significant difference in both the percentage distribution of impacts and

absolute values between zones ($p < 0.0001$) (Figures 8.1, 8.2 and 8.3). Absolute values did, however, show significant difference between zones for changes of direction (Zone 5, $p = 0.007$, 0.0 ± 0.0 , $d = 1.67$; Zone 6 ($p = 0.011$, 0.2 ± 0.4 ; $d = 1.57$) and accelerations (Zone 5, $p = 0.018$, 0.7 ± 1.3 , $d = 1.07$; Zone 6, $p = 0.049$, 1.5 ± 2.2 , $d = 0.98$). Despite no significant difference being noted for accelerations and decelerations between zones for percentage distribution, decelerations did follow the pattern of a decreasing frequency of impacts as the magnitude increased, yet accelerations revealed a greater distribution of impacts in Zone 6 (Frequency = 2.2; Distribution = 15.8%) compared to Zone 5 (Frequency = 0.7; Distribution = 12.8%) (Figures 8.1 and 8.3). Upon further assessment of impacts occurring from changes of direction, accelerations and decelerations, separately from those incurred from collision, it was found that decelerations accounted for the greatest proportion of these explosive movements in Zone 4. Due to the likelihood of change of direction, acceleration and deceleration movements appearing in Zone 4, one could perhaps question the relevance of these match demands for creating fatigue, when compared to impacts accrued by collisions. Despite the high frequency of changes of direction, accelerations and decelerations within a rugby player's match demands, the need for practitioners to focus upon the more likely fatigue inducing collision elements of the game are paramount, as these are the match demands that are most likely to limit future optimal training ability.

Research upon which to compare the results from this study is sparse. The well documented research by McLellan and Lovell (2012) has been referenced in many recent investigations of impacts from team sport settings (Cunningham et al., 2016; Jones et al., 2015; Wellman, Coad, Goulet, Coffey, & McLellan, 2016; West et al., 2014), however, it is important for practitioners to note that their research only involved collision impacts. As prior research did not include impacts incurred from accelerations, decelerations and changes of direction, and solely those that involved collisions, the comparison of impact frequencies between the studies would be ill advised. In addition to the research by McLellan and Lovell (2012) not involving accelerations, decelerations and changes of direction, the impact zones classifications (measured in G) were different to this study. The differing impact zone classifications between studies, combined with a difference in GPS unit specification, mean that the frequency and magnitude of impacts assigned to each study are likely to be misaligned. Future research should therefore perhaps consider the alignment of GPS impact zones between studies to enable better comparison of data.

When considering the results from Chapter 3, detailing the match demands required for positional groups, the distances covered are perhaps not surprising and cannot be considered abnormal when viewed alongside other research (Cahill et al., 2013; Lindsay, Draper, et al., 2015; Quarrie et al., 2013). However, in contrast when assessing the large contribution of impacts from collisions in Zone 4 (Frequency = 15; Distribution = 32.7%) noted within this experimental study, it could be argued that the high intensity collision efforts are extreme in frequency (Figures 8.1 and 8.3). This unexpected finding has implications for the assessment of likely fatigue which, when considered alongside the findings from Suarez-Arrones et al. (2014), which indicate that contacts induce greater internal loads (measured via heart rate response) to that accumulated from running, the influence of collisions on restoration of performance and the role that analysis of impact data can have upon this interpretation is further emphasised. In addition, the recommendations by Reardon et al. (2016) are of importance for future considerations, as assessment of collision counts in rugby union should perhaps investigate smaller G-force increments. These assessments of smaller G-force increments would develop a

better understanding of micro-technology collision classification and therefore potentially avoid the false positives seen within this experimental study, when assessing impacts. Lastly, a potential point for consideration is that results from this experimental study, in particular that of Chapter 3, would indicate that elite level rugby players (and specifically the backline players), need to be conditioned to able to perform a high frequency of changes of direction, accelerations and decelerations within training and match play. If elite backline players are not conditioned to perform these demands, it could be argued that avoidance of injury and achievement of optimal performance will be sub-optimal.

8.5.3 Impact categorisation

Based upon the results of this study, the notion that GPS calculates impacts accurately can be questioned. Future practice should perhaps include the analysis of a collision load metric, as sole impact values do not illustrate the full magnitude of the match demand experienced. It could be argued that a collision load metric would provide more detail upon match demands' likely influence upon restoration of performance, as this metric would involve the sum of the speed and duration of the collision and the magnitude of the impact involved within the collision. Similarly to the findings of this experimental study, previous research (Suarez-Arrones et al., 2014) has shown disparities between collisions recorded via the GPS units and those coded from video recordings, with non-significant correlations reported ($r < 0.42$, $ES > 1.4$). The notion that high magnitude impacts encountered during rugby match play involve only collisions, is disputed within this experimental study. Support for this is also presented by Gabbett, Jenkins, and Abernethy (2011), who noted that the average number of impacts performed by individual players were considerably greater than the total number of collisions typically performed during match play, further suggesting that impact data to assess collisions specifically data should be interpreted with a degree of caution. Additionally, when considering that Reardon et al. (2016) noted in unpublished findings that accelerations are likely to be mistaken for collisions, due to the G-force experienced and the tilt in body orientation associated with acceleration actions, the questionable accuracy of impact data is further emphasised. This notion of accelerations likely to be mistaken for collisions could be explained by an over-coding of impacts at the 2 G threshold, as represented by the large frequency of impacts associated with accelerations within this study.

A player load variable has been researched by Cormack et al. (2014), with this methodology regularly generated and updated by GPS providers and used by many team sport practitioners to monitor players. Player load values measure the combined load across three movement planes measuring accelerations and decelerations, yet the exact algorithms and the reliability of such metrics is unknown and therefore warrants caution prior to implementation. These "load" values are calculated by the rate of change of directions in the upward, downward and lateral directions, allowing three dimensional measurement of activities, such as jumping and impacts in team sport settings to be measured, providing a measure of total load applied to a player in matches or training. It is, however, important to note that a collision load metric needs further investigation to assess its applicability for use in the analysis of rugby union match demands.

8.5.4 Limitations of the research

It is important for practitioners to note that the nature of this study is subjective and that the results are only a representation of the individual players in question. The use of only one player per assessment of impact frequency and magnitudes for each position was a limitation of this study, yet the time consuming nature of this analysis and the "real world" nature of the

elite setting from which the impact data was taken were major determining factors in the testing protocol implemented. It is commonly seen in professional rugby, that some players playing the same position perform their role within a team in different ways, based upon team tactics and their own individual strengths and weaknesses. As a result of these individual playing styles, it is unlikely that the match demands for two games are going to be the same and the individual nature of the data collected would therefore have implications, meaning comparison between differing data sets is discouraged. Similarly, the comparison of forwards and backs could not be conducted within this experimental study, due to there only being nine data sets (one per position group). However, it could be argued that the likely difference in impact data between groups was accounted for via normalised percentage calculations of each collision. This notion of differences occurring across positional groups and the use of normalised percentage calculations is therefore an additional consideration for future research.

Despite sample sizes being low in chapters 4, 5 and 6, the associated effect sizes support the findings from these experimental chapters, which when considered alongside the notions of Buchheit (2016) disputing the sole use of p values further reinforce recommendations. In addition to the low sample size being a limitation of this study, the notion that the results presented being only a reflection of the assessors' interpretation of the movements performed while incurring impacts, is also a limitation. Despite the assessors' definition of movements being consistent throughout the analysis, it would be recommended in future practice that multiple researchers should be used to assess the data and improve inter reliability as was recommended by Austin, Gabbett and Jenkins (2011). Similarly, despite all players wearing the GPS unit in the same position between their shoulder blades, the discrepancy noted between some players wearing tighter fitting playing shirts than others, and some players wearing their GPS units in a "GPS vest" was also considered a limitation of this study. Assessment of the GPS files created alongside the video enabled the coach to use the naked eye to view movement instances where impacts occurred and it is the assessor's belief that some players' GPS units were perhaps more sensitive than others. This sensitivity was perhaps not due to the inter reliability of GPS units used, but was most likely explained by the way in which the GPS unit was sitting between the shoulder blades. On assessment of the GPS file alongside the video it was evident that many impacts above Zone 4 were accounted for by foot strikes on the playing surface for some players but not for others, therefore supporting the view that the fit of the GPS unit between the shoulder blades was a determining factor in the sensitivity of the frequency and distribution of impacts generated. This notion was supported in recent research (Barrett et al., 2016) which illustrated the influence of wearing a GPS unit either at the scapula area or closer to the player's centre of mass. Results from Barrett et al. (2016) in simulated soccer match play indicated that lower limb movement strategies taken from GPS units positioned at the scapula should be taken with caution, as greater contributions to vertical forces were noted in data taken from the scapula compared to those taken from the centre of mass.

8.5.5 Future research directions

As was conducted within this research, absolute values of impact frequency and magnitude should perhaps be used alongside those detailing percentage distribution in order to better guide practitioners in future training prescription. When "eye-balling" the results, percentage distribution values for collisions were noted to be vastly different between Zones 4, 5 and 6, yet no significant difference was noted in the analysis of the results. In contrast, when assessing percentage distribution values for changes of direction significant differences were noted, despite not being indicated by initial viewing of the relevant raw data. However, when

assessing the absolute values for all four metrics (changes of direction, accelerations, deceleration and collisions) it is apparent that more differences in their frequency do exist. Practitioners are therefore advised to use absolute values alongside percentage distribution, as it could be argued that the percentage distributions of where impacts occur is misleading. In addition, it could be argued that the frequency of impacts from collision is of more concern for post-match analysis than the percentage distribution. A high frequency of impacts from collision would most likely indicate a longer time-course of restoration of performance, yet percentage distribution could mislead practitioners in this assumption.

Many of the impacts recorded during foot strikes are likely to be vertical accelerations and decelerations and not horizontal impacts, despite this being the direction in which the player is moving. These vertical impacts during low intensity movement in match play are therefore presenting problems for practitioners when assessing the frequency of impacts generated \geq Zone 4. A player could display a large volume of impacts, but if many of these impacts are vertical in nature (and perhaps a result of foot strikes), the likely fatigue created is going to be less than if they were attributed to collisions. The notion of vertical impacts being of relevance when assessing likely impact load was also noted by Hausler, Halaki, and Orr (2016) and it could therefore be argued that the analysis of impacts attributed to either locomotion or collision is required. In addition, this analysis of impacts attributable to specific match demands would benefit from the assessment of absolute values, alongside those from percentage distributions. Lastly, when considering the likelihood of differing match demands between players playing the same positions, impact profiles should perhaps be different both within and between playing positions. This would mean that the analysis of individual impact data would be more accurately classified and accepted for continued use across elite rugby settings.

8.6 Practical applications

Results from this study are innovative and add to the knowledge of impacts encountered during game play. However, from this research it could be argued that the values presented from GPS outputs alone cannot be taken at face value, as erroneous interpretation of impacts of high magnitude may be incorrectly identified as collisions. Due to the data collection issues highlighted above regarding impacts, it is important for practitioners to not only view the values exported from GPS software, but to instead sync the values with video footage. Varying relationships in fatigue created between impacts occurring with and without collisions are likely, meaning a recommendation for future practice in the assessment of how the impact occurred. It is correct for practitioners to note that all impacts experienced during match play are likely to be fatiguing, but the notion that impacts need to be classified is warranted, as some impacts will impose more fatigue than others depending upon the match demands and movements involved. When considering that almost 25% of high magnitude impacts consisted of accelerations, deceleration and changes of direction, the relevance of the impacts to time-course of restoration of performance needs investigated further. Despite the above limitations existing for the use of GPS data, the ability to assess intensity and prescribe restoration practices from the technology currently available is essential for practitioners in the elite field. This assessment of match demands incorporating GPS impacts within elite rugby union is therefore likely to continue. As a result of the evidence presented in this experimental study, the accuracy with which practitioners could plan future training post rugby union match play is questioned. Based upon GPS data alone, the information provided might not present a clear

picture of the match demands experienced and therefore a practitioner's ability to make informed decisions upon resultant fatigue is blurred. The use of both video and GPS data will provide a greater representation of match involvements and their likely influence upon fatigue post-match, with percentage distribution and absolute values being key to this interpretation.

9 Thesis discussion

9.1 Introduction and recap of existing research

The literature review conducted provides detail surrounding the physiological cost of rugby union game play and the tests that are commonly used to assess measures of fatigue post-match. However, this review of current research showed that no commonly used monitoring tool or protocol exists with regards to the assessment of recovery and restoration of performance in the days post rugby union game. Current research proposes that differences in movement patterns and activities undertaken by positional groups do occur, with recommendations that forwards should be provided with more time to recover post-match than backs, given the greater contact loads they sustain and subsequent longer time-course restoration of performance (Quarrie et al., 2013). Prior research intimated that mechanisms of fatigue are wide ranging (chronic and acute) (Alaphilippe et al., 2012; Jones et al., 2014; Lindsay, Lewis, Scarrott, Gill, et al., 2015; West et al., 2014) and that meaningful levels of fatigue need to be detected via both subjective and objective performance testing, such as CMJ and WB, in order to better advise practitioners.

As identified within this literature review, methods of measuring performance are vast in quantity and applicability to the sport setting in question, with measures of neuromuscular function, hormonal markers, heart rate derived measures and sub-maximal testing often being utilised. This literature review enabled the identification of CMJ testing and self-reported well-being measures as tools for monitoring restoration levels post rugby union match play. This choice of monitoring tool was mostly dictated by methodological and logistical considerations, and the series of investigations that followed measured their reliability and relevance to elite rugby settings. The knowledge gained regarding match demands and the likely fatigue response created will enable coaches in elite rugby to make more informed decisions upon timing, frequency and intensity of training in the days post-match. Prior research has not included match characteristics for players that have played less than the entire game (< 80 minutes), yet the inclusion of match characteristics for players that have played reduced minutes would better guide elite environments upon resultant physiological cost. Lastly, a process of combined data collection including both GPS data and video recordings was implemented within this thesis, to provide more detail surrounding the individual position-specific movement patterns and the likely resultant affect these match instances have upon fatigue levels. Recent research in rugby league identified impacts > 7 G as important for consideration of timing, frequency and intensity of training in the days post-match (McLellan & Lovell, 2012). The final experimental chapter of this thesis therefore investigated this theory within elite rugby union, in an attempt to identify which match demands are most likely to induce these high magnitude impacts.

9.2 Major findings of the research

Despite many of the experimental chapters within this thesis investigating topics that have been detailed previously, the combination of GPS and video analysis techniques and the testing protocol implemented provided new findings in the match demands experienced by elite players and are therefore of importance for future practice. The match characteristics revealed within the initial experimental chapter are perhaps not surprising when considered alongside earlier research in the area (Cahill et al., 2013; Coughlan et al., 2011; Jones et al., 2015; Lindsay,

Draper, et al., 2015; Venter et al., 2011), yet the evidence presented shows many previously unreported differences between forwards and backs, potentially based upon the incorporation of data from players that played less than 80 minutes. This broader assessment of game minutes provides rugby union coaches with a more true representation of match demands, across varying match durations, which can then be applied to future prescription of training and monitoring methodologies.

When assessing absolute values, no significant differences were observed in the frequency of impacts > Zone 3 between forwards and backs. This non-significant difference in the frequency of impacts > Zone 3 is perhaps surprising, when considering forwards' typical match involvements. However, when taking into account the reduced match minutes performed by forwards (Chapter 3) and the higher magnitude impacts associated with collision activities during match play (Chapter 8), the results are of added value. Backs were observed to perform at a higher intensity during match play (70.9 ± 7.4 m/min) than forwards (64.0 ± 6.3 m/min; $p < 0.001$, $d = 1.00$), with backs also completing a greater number of accelerations (32.2 ± 10.6) compared to forwards (22.0 ± 11.9 ; $p < 0.001$, $d = 0.88$) and a greater number of decelerations (41.9 ± 12.3) compared to the forwards (30.8 ± 14.4 ; $p < 0.001$, $d = 0.82$). In contrast to the hypothesis, results from this study also show that backs experienced a greater total number of impacts than forwards (Forwards 3176; Backs 5501), however this study does support the view that forwards are involved in more "heavy" impacts (> Zone 3) (Forwards 229 ± 160 ; Backs 226 ± 151). It was also of note within this research, that forwards experienced a significantly greater number of Im6 when compared to backs, which when considering these Im6 instances represent a 13-15 G involvement, the resultant physical effect this must have upon the players involved is apparent.

Despite many of the match demands assessed in this research being lower than those previously reported (Cahill et al., 2013; Coughlan et al., 2011; Lindsay, Draper, et al., 2015; Reardon et al., 2015), the influence of relative assessment is likely to explain this. For example, forwards in this research were noted to compete for 66 minutes on average, which is lower than the whole match duration figures reported in other similar studies. The incorporation of relative measures was, however, considered more applicable for match demands assessment, as it could be argued that this study is perhaps more representative of modern rugby union where players are often asked to play less than the full match duration. As reported in Chapter 3.5, consideration of both absolute and relative measure is of importance. The relative values for forwards are perhaps of more interest than the backs when assessing the data displayed above in Tables 3.4-3.9, where some variables may present more information from a relative view rather than an absolute. This notion of relative position-specific assessment may help better guide practitioners in future match demand analysis.

Of specific interest from this research, were the findings that showed that differences in match demands occur between the nine positional groups. Specifically, props typically experienced the lowest number of impacts in the lower impact zones (Im1, Im2 and Im3), yet also experienced a large number of Im6 values. Similarly, full backs showed a large number of impacts in the high impact zones (Im4, Im5 and Im6), yet they also experienced a large number of low-level impacts. The positions of hooker and back row also illustrated a large number of Im6 values when compared to the values they experienced at the lower impact zones. This may not be surprising considering their typical match involvements, yet it adds weight to the notion that forwards experience more high magnitude impacts than backs and that impact demands also differ between forwards' positional groups. These results therefore provide a greater

understanding in respect to the likely blunt trauma resulting from match demands and should help guide practitioners in planning strength and conditioning programmes for positional groups.

Chapters 4, 5 and 6 assessed jump modalities, regarding their reliability and practicality for use within elite rugby union settings. Similarly to what has been reported in prior research (Markovic et al., 2004), results from Chapter 4 identify CMJ as the jump modality that illustrated the highest reliability both within (ICC 0.938) and between-session (ICC 0.906) across testing days, in comparison to the SJ, SLDJ-L and SLDJ-R. Alongside CMJ being a previously identified jump modality for use in restoration of performance testing (Gathercole, Sporer, Stellingwerff, et al., 2015b), the results of this thesis support the notion that CMJ provides the most sensitive and reliable data for jump performance monitoring in elite rugby union settings. Evidence collated within Chapter 4 showed that CMJ demonstrates the lowest SDD (1.7%) between sessions when compared to SJ, SLDJ-L and SLDJ-R and therefore adds to the knowledge base. However, perhaps most relevant from this experimental chapter was the finding that a change in jump height of $\geq 1.7\%$ was meaningful for CMJ performance and that this value should be used for future practice in the subject area.

As a result of CMJ being identified as the jump modality that exhibits the highest reliability within and between sessions, the subsequent experimental chapter aimed to assess the use of CMJ measurement on an *OptoJump* compared to that on a force plate. The force plate is considered the “gold standard” tool for jump measurement, yet results from this experimental chapter indicate that the use of *OptoJump* is also reliable (CV < 10%). Within Chapter 5, a significant correlation ($r = 0.906$) was noted between *OptoJump* CMJ height and CMJ height measured on a force plate, therefore supporting the reliability of future *OptoJump* use. Results from Chapter 6 examining a single CMJ showed high reliability (CMJ ICC = 0.986, SDD 2.4%), with no significant differences ($p > 0.05$) in jump height observed between days. Despite Chapter 4 showing differences existing between session one and session two, when assessing CMJ performance, Chapter 6 shows that the performance of a single CMJ (measuring jump height) is a reliable measure. Therefore, as was also noted in Chapter 5, the findings from Chapter 6 support the performance of a single CMJ (measuring jump height) on an *OptoJump* as a reliable measure for assessing post-match levels of readiness, when a force plate is not readily available. This finding is therefore of importance for guiding future jump assessment in elite rugby settings.

The final experimental chapter utilising jump assessment was Chapter 7, which aimed to identify meaningful change in CMJ and self-reported well-being scores. Due to the findings of the previous experimental chapters, CMJ height had been noted as reliable and applicable for use in elite rugby union settings and therefore warranted further investigation regarding expected change post-match play. Results from Chapter 7 showed that both CMJ performance and WB score were reduced at 60 hours post-match, 90 hours post-match and 170 hours post-match, with interestingly WB scores reduced to a greater value and for a longer time-course than CMJ. A meaningful change of 2.6 cm (-6%) in CMJ performance was noted alongside a -9% change in the WB score at 60 hours post-match, therefore adding to the knowledge base of existing research surrounding the time-course of recovery post match play. Despite correlations noted between D6 ($p = 0.044$; $r = 0.950$) and accelerations ($p = 0.001$; $r = 0.953$) at 60 hours post-match with changes in CMJ performance for the forwards, evidence from this study would dispute the views of previous time-course research (Quarrie et al., 2013), which reported that a longer recovery time-course would likely be associated with forwards

compared to backs. As a result of this experimental chapter, practitioners are therefore advised to consider backs as having a longer time-course of recovery. In conjunction with this, the match demands of positional groups may also guide the length of recovery post-match and therefore the use of GPS data warrants consideration, alongside performance change measures, when assessing players' readiness post-match.

Lastly, within Chapter 8, as was hypothesised, collisions accounted for higher magnitude impacts than other movement match demands. However, new findings from this research, combining video and GPS data, do show that the reliability of the classification of impacts identified within this study are a concern, as individual player movement patterns and the resultant output provided from the GPS were noted to provide misleading information. Additionally, the frequency of impacts experienced as a result of acceleration and deceleration were shown to be an important consideration for future training prescription and analysis of likely restoration of performance in the days post match play was noted as a new finding and one warranting further investigation. As a result of this experimental chapter, practitioners working in the elite field are therefore recommended to combine video and GPS data, whilst also incorporating both absolute and relative values. This methodology should help to develop a greater representation of the match involvements assigned to impacts experienced during match play, as the values presented from GPS outputs alone cannot be taken at face value.

9.3 Limitations of the research conducted

9.3.1 "Real world" limitations

The main limitation of this research involves the lack of multiple time-points post-match upon which change in CMJ performance and WB scores were assessed. Sixty hours post-match was the most comparable time point between that of previous research and this thesis, yet it is clear that including time points prior to and post the 60 hours post-match would have provided added value. The inability of the author to gain additional time-points prior and post to the 60 hours post-match was due to logistical constraints of the players' training schedule, meaning access to players for assessment was limited. A further "real world" limitations that prevented the collection of additional data, that would have benefitted the results, was that the data was collected from only one team. Despite the data collected adding to the knowledge of match demands within rugby union in the northern hemisphere, the limitation of the data being from only one team is a point for practitioners to consider when they are examining the results. However, as previously discussed, the direct competition that exists between many teams within Europe, means that sharing of inter-team data may be unlikely and that this limitation is therefore unlikely to be resolved in future research.

Additionally, a point for consideration and potentially another "real world" limitation of this thesis was that despite all the games and weekly training structures within this research being consistent, some games involved more travel than others, meaning the effect travel could have had upon subsequent CMJ performance and well-being needs further investigation. This notion of travel upon performance decrement was noted in recent research from the southern hemisphere (George et al., 2015), where travel resulted in more missed tackles and (1.7 ± 1.3), less gain line success in the first half of games (-3.0 ± 1.9) and less points scored in the second half of games by away teams. Similarly, in youth soccer players, large positive correlations ($r = 0.70-0.87$) were noted between well-being and distance travelled to away game location. Travel or lack of travel between home and away games could therefore have been a limitation of this thesis, yet similarly to the limitation regarding limited time points for performance

assessment, logistical constraints surrounding the players' seasonal schedule were the main determining factor in the choice of games to be assessed.

The above issues detailing limitations associated with the logistics of the "real world" setting within which this research was conducted, are an important consideration. However, readers need to consider that this thesis and any future investigations need to be ecologically valid to be applicable in the applied setting. Therefore, the concerns surrounding the lack of additional time-points for assessment of restoration, the potential issues surrounding travel and the notion that the data from this thesis is only representative of one team are perhaps accounted for. The idea that any future studies can be implemented into an applied setting and that the testing protocol could guide the training schedule within which assessments are taking place is naïve. It is unlikely that rugby coaches working in the elite field will allow for alteration of training schedules purely for in order for testing to be conducted and the potential conflict this intervention could cause as a result of trying to implement such plans, means that this is a situation that should be avoided.

As a result of such "real world" issues, the informed selection of CMJ and WB as tools to assess restoration in this elite setting was mostly guided by logistical influences. Once reliability was noted for these measures, the rationale for their use was warranted. It could be argued that other performance tests could have provided more information upon restorative state than CMJ and WB, yet the logistical issues surrounding such tests would have outweighed the benefit of their inclusion. For example, this thesis could have conducted twitch potentiation on an isokinetic dynamometer as this would have been a more accurate measure of fatigue, yet logistically it is unlikely that this form of testing would have worked within the applied setting in which this thesis stood. The unstructured nature of training weeks throughout a rugby union playing season and the logistics that surround management of a squad of fifty-plus players, make these forms of intricate testing impractical. Elite sport is an ever-evolving setting and a logistically difficult scenario within which to conduct research, with practitioners advised to be aware that a sound study design is often more realistic than a perfect one.

9.3.2 Limitations of CMJ protocol implemented

As discussed above (Chapter 9.3.1), a major limitation of this thesis was the inability to test the players at additional time-points post-match, with this therefore having an influence upon the CMJ testing protocol implemented. However, as noted, the "real world" limitations associated with daily access to elite players dictated the time-points selected. Another possible limitation with this study when considering the evidence presented by Gathercole, Sporer, and Stellingwerff (2015), is that the analysis of CMJ performance was only focused upon outcome-related variables. As discussed previously, Gathercole, Sporer, Stellingwerff, et al. (2015a) argued that outcome driven CMJ analysis does not assess the later element of the SSC-recovery pattern and therefore overlooks some key information. Based upon this research by Gathercole, Sporer, Stellingwerff, et al. (2015a) it could be assumed that rugby players adapt their CMJ strategy to avoid any decreased jump height value being presented, despite NMF existing. For example, a player may adjust their eccentric depth and resultant concentric force during CMJ execution, dependent upon their current neuromuscular function. Within this thesis, it could therefore be argued that the lack of decrement shown in jump height for forwards compared to backs could be explained by the movement strategies of subjects not having been assessed. The results of Gathercole, Sporer, Stellingwerff, et al. (2015a) do not dispute the notion that CMJ testing is a suitable test to detect fatigue-induced changes in NM function, yet it does recommend analysis of both typical CMJ variables (jump height) and

kinetic variables (RFD) to provide a more detailed analysis reflecting both CMJ output and movement strategy employed. It is, however, the author's view that the aforementioned logistical and financial implications of assessing CMJ performance using kinetic measures do not warrant the use of a force plate.

The implementation of recent research regarding the inclusion of kinetic variables (Claudino et al., 2016; Gathercole, Sporer, Stellingwerff, et al., 2015a; Kennedy & Drake, 2017a; Kennedy & Drake, 2017b; Roe et al., 2015) within future practice is warranted and its omission could therefore be included as a potential limitation of this thesis. However, when considering that ultimately this thesis aimed to assess whether players had restored performance prior to the next game (as measured by pre and post-match jump height), the strategy for how they achieved this jump height is perhaps irrelevant. It could be argued that players may achieve this jump height via a different strategy and in a different movement pattern, which although informative is immaterial to this thesis. The impulse players create during CMJ performance will determine their velocity at take-off and therefore the notion that you can adopt two different strategies of CMJ to create the same impulse (by producing lower force over a greater period of time or a higher force over a shorter period of time), should be considered. This impulse (calculated by multiplying force by time) will result in the same acceleration, the same velocity of take-off, and will therefore yield the same jump height, making the strategy of movement unimportant. Despite the strategy employed, if players are noted to have restored CMJ height back to prior performance levels, it could then be assumed that this jump height could be transferred to the field and therefore utilised to achieve a positive outcome (winning a lineout for example). At present, the disadvantages of using a force plate still outweigh the advantages and it is unlikely that all team sport practitioners will invest in such technology despite the evidence presented above. The implementation of such jump assessment protocol depends considerably upon the level of financial and scientific support available to the practitioners. This combined NMF assessment approach typically requires a force plate for assessment and therefore limits the majority of rugby teams, due to both financial and practical implications of its use in the elite field on a daily basis.

Considering the restoration of performance assessments conducted within this thesis surrounding the use of mean squad CMJ values, highlights another potential limitation. Evidence to support the use of individual assessment of CMJ performance, instead of mean squad CMJ values, was presented by Gathercole, Sporer, Stellingwerff, et al. (2015a), who noted that different individuals exhibit marked differences in recovery profile post fatiguing exercise and that the NMF response elicited during CMJ performance must therefore also be individualised. Additional support for individualised jump testing was presented by Hamilton (2009), who noted limited worth in assessing mean squad jump values and instead recommended that practitioners focus upon individual scores to accurately measure fatigue pre and post soccer match. It could be argued that implementation of individualised jump testing, alongside the recommendations of Roe et al. (2015) to use mean values of two or three jumps, would perhaps provide improved reliability and sensitivity in comparison to an individual jump measuring a maximal jump height value.

Lastly, a future direction of jump testing protocol to assess NMF and therefore a potential limitation of this research surrounds the use of a DJ. Despite a unilateral SLDJ being examined in Chapter 4 and considered to be unreliable (SLDJ; ICC 0.759 - 0.875) and therefore impractical for use in applied settings, the potential use of a DJ that is bilateral should perhaps be considered in future investigations. It could be argued that a DJ that encompasses bilateral

landing and take-off, enables increased sensitivity in part due to a DJ using both contact and flight time measures. The results from Chapter 4 and the views of Hamilton (2009), who noted incorporation of DJ-RSI being a performance test capable of assessing NMF, were considered when deciding upon which jump performance tests to include, yet the rationale for a SLDJ can now be questioned. The reasoning behind the incorporation of SLDJ at the commencement of this thesis, was that Harman et al. (1990) reported that unilateral jump performance had a stronger relationship with sprint performance than bilateral jumps. In hindsight it could now be assumed that the assessment of impaired neuromuscular function may have been better assessed via utilisation of a bilateral DJ. The results from Chapter 4 and the unpublished views of the author, noted that the technique adopted during the SLDJ differed mostly on the start of the jump where some players were noted to “drop off the box” and some were noted to “jump off the box” onto the landing surface below, meaning a discrepancy in results was likely. Utilisation of a bilateral DJ would have still assessed the relatively short contraction times involved in such a movement, yet would have provided less opportunity for altered technique as associated with the SLDJ and therefore may have led to more sensitive measures.

9.3.3 GPS limitations

Despite GPS being a commonly used tool to manage training load in many elite rugby settings, evidence from this research illustrates that limitations to its use do exist. Firstly, it appears that much of the data collected and subsequently produced by GPS units surrounds the use of accelerometer data. Many GPS providers have recently added metrics utilising gyroscopes alongside accelerometer data, yet as is illustrated by this research the reliability and practicality of their use can be questioned. Results from this study would support the views of Chambers, Gabbett, Cole, and Beard (2015), that GPS is capable of assessing sport specific movements, but the ability of GPS to quantify collision elements of rugby union match is still unwarranted. Within *StatSports Viper* software, a rugby specific collision metric has been developed to quantify when a collision has occurred, by using the gyroscope and the accelerometer data. Essentially, this metric is derived from the gyroscope experiencing a tilt in its axis (as is commonly seen during collision movements by players in rugby) and an impact registering in the accelerometer within a similar timeframe, with the magnitude of the collision determined via the speed and duration of the collision. The collisions are therefore categorised via a weighting system within the software, yet the specifics of these weightings are not disclosed to end-users. Results from this study would, however, dispute this metric, as it was noted for one of the players assessed that multiple collisions were incorrectly assigned to him, when he simultaneously decelerated as he approached a ruck (therefore accruing an impact) and bent over to pick up the ball.

The use of a sole metric can therefore be classified as a limitation of GPS use, with the algorithms that quantify collision metrics using gyroscopes, for example, requiring further investigation. Research within other team sports (Gabbett et al., 2010; Gastin, McLean, Spittle, & Breed, 2013) used only the gyroscope to assess player collision movements and did not use the sum of rotational forces from the gyroscope in combination with the sum of perpendicular forces from the accelerometer also housed within the GPS units. Despite research existing (Kelly et al., 2012) to confirm the reliability of correctly identifying collisions in elite level rugby union (recall and precision rating 0.933 and 0.958 respectively), no evidence has currently been reported to support *StatSports Viper* software in the analysis of collision instances. In addition, when considering the perceived reluctance of many software suppliers to provide detail in the quantification of impact and load collated by GPS units, the need for a more

thorough examination of impacts, their occurrence within game play and the incorporation of this data within GPS data analysis is emphasised. Future development of collisions detection within the software and the validation of impact forces will improve the applicability for use in elite rugby settings.

Despite it not being the focus of this thesis, the lack of validity of the assessment of collisions as a reliable metric of use in rugby union, is a concern and is consistent with the findings of Hausler et al. (2016). Similarly to as seen in this thesis, Hausler et al. (2016) conducted a meta-analysis of GPS technology and revealed that inconsistencies are evident between collision identification and categorisation between magnitudes. However, in a review comparing a micro-technology unit (*minimaxX*; *Catapult Sports*) with video-based coding of the actual collisions in elite rugby league (Gabbett et al., 2010), no significant differences were detected. Despite correlations not proving validity, Gabbett et al. (2010) observed strong correlations ($r = 0.96$, $p < 0.01$) between collisions recorded via the *minimaxX* units and those coded from video recordings, therefore demonstrate that the *minimaxX* micro-technology units offer a sound method of quantifying the contact load of collision sport athletes. Yet, more recently, disparities between collisions recorded via the GPS units and those coded from video recordings, were noted within rugby sevens match play (Suarez-Arrones et al., 2014) with non-significant correlations reported ($r < 0.42$, $ES > 1.4$). The differences in findings between these studies could, however, be explained by the technology used, the study populations involved and the experimental conditions, as not only did the sport differ, but so did the context (training or match).

Upon viewing the matches used for assessment within this study, it was noted that the way in which the impact from a collision experience is categorised (Zone 4 to Zone 6) often depends upon the orientation of the way the collision is made with the ground or the opposition. When viewing individual collision instances that accrued high magnitude impacts, it could be argued that if the opponent is moving in the same direction as the attacker or defender, this is likely to have an influence upon lessening the magnitude of impact assigned to them. Within the individual analysis of player files, some players were seen to make a tackle, yet the tackle completed registered as < 9 G and therefore was not included within the final analysis of where impacts occurred. However, when assessing some accelerations conducted by players, it was noted that on multiple occasions some of these acceleration instances registered as > 9 G. These results may be correct, but on viewing the video instances for these movements the researcher would question this, when comparing these match instances to collision instances that did not register as high impact values. When considering that collision metrics developed within the software often involve high magnitude impacts, the applicability of impact magnitude and its use for assessment of match demands and future training prescription can be questioned. Collision profiles should perhaps be different across playing positions and the identification of collision zones more accurately classified and accepted for use across elite rugby settings.

Another area of investigation within GPS classification that warrants investigation is the weighting of movement tasks. As was evident when viewing the video files encompassed in Chapter 8, it could be argued that movement demands that elicit impacts in the GPS unit should not be globally weighted. A landing from a jumping movement from a player that elicits a Zone 6 impact, for example, will be unlikely to have the same fatigue effect as a Zone 6 impact from a collision situation. This notion therefore warrants further investigation, especially when

considering the individual frequency of impacts produced via movement dynamics discussed. These findings would therefore further lend towards the view that absolute values need to be accounted for in analysis of GPS impacts and not solely percentage distribution, as the likely fatigue response from collisions is going to be longer lasting than those attributed to other movement tasks. Lastly, within this thesis, the discrepancy noted between some players wearing tighter fitting playing shirts than others, and some players wearing their GPS units in a “GPS vest” is considered a limitation of GPS research.

9.4 Practical applications and future research directions as a result of the research conducted

9.4.1 Future jump testing protocol to assess restoration of performance

This thesis identified CMJ as applicable in the assessment of restoration of performance testing and its use in many elite settings is likely to continue. Findings from this thesis further the recommended protocol for CMJ testing in measuring fatigue, with a change in jump height of $\geq 1.7\%$ being noted as meaningful. Results collected within this thesis also support the performance of a single CMJ (measuring jump height) on an *OptoJump* as a reliable measure for assessing post-match levels of readiness, when a force plate is not readily available. Perhaps most importantly for future implementation of CMJ testing, was the finding that reduced CMJ performance was noted at 60 hours post-match, 90 hours post-match and 170 hours post rugby union game. This finding would therefore support the notion of reducing training volume in the days immediately post rugby union match play, yet would also support previously unpublished observations that elite rugby players often do not restore performance prior to the next game commencing and that players often play in a sub-optimal state. As a result of this thesis, recommended time-course of recovery is therefore noted to be longer than that shown from previous research (West et al., 2014) and should be a major consideration for rugby administrators when scheduling fixtures. In addition, a finding from this research that needs to be considered within future CMJ testing protocol is the discovery that backs have a longer time-course of recovery compared to forwards. Considering that this finding disputes the views of previous time-course research (Quarrie et al., 2013), which reported a likely longer time-course of recovery associated with forwards compared to backs, the need for positional CMJ testing protocol is perhaps required.

As was incorporated within this research, the majority of studies have used the highest CMJ performance to assess fatigue, with recent research adding support to the use of jump height to assess neuromuscular status (Claudino et al., 2016). It is clear from the results in the experimental chapters above, that utilising CMJ as a fatigue test provides added value to the protocol that should be implemented in the days post rugby union match play. Despite this series of investigations proposing the use of a sole CMJ (mainly due to logistical constraints), recent evidence presented, regarding the number of repetitions and average measures (in contrast to highest values), are also important for consideration within future jump testing in assessing fatigue. Perhaps most interesting based upon the meta-analysis conducted by Claudino et al. (2016) is that averaged jump results (of repetitions conducted) were reported to be more sensitive than the highest single jump, in detecting fatigue. Research by Roe et al. (2015), discussing CMJ protocol for NMF assessment, is also of note for future implementation in elite applied rugby settings. Roe et al. (2015) reported that CMJ metrics are reliable ($CV < 5\%$), when assessed with two or three repetitions of a CMJ. The results presented by Roe et al. (2015) support the earlier findings (Cormack, Newton, McGuigan, & Doyle, 2008) that mean

force was capable of detecting SWC, however, it is still important to note that the findings of Cormack, Newton, McGuigan, and Doyle (2008) are taken from a single CMJ protocol, therefore illustrating a lack of commonly used CMJ protocol.

Perhaps the most important consideration for practitioners when implementing CMJ to assess NMF, are the views of Gathercole, Sporer, Stellingwerff, et al. (2015a), who questioned the use of CMJ height. Gathercole, Sporer, Stellingwerff, et al. (2015a) instead recommended using variables that assess changes in jump performance outcome, but also variables that assess changes in the movement economy of the athlete in question. CMJ could be considered a slow SSC activity and therefore its use for detecting the higher-end more explosive and neural fatiguing elements of readiness could be questioned. The inclusion of kinetic variables to monitor NMF responses, which differ in focus based upon circumstances (intensity, duration and type of activity), is potentially the next area of focus for research in restoration of performance in elite level rugby union. The results from this thesis do support jump height for measuring NMF in the days post rugby game, yet practitioners should consider that NMF may also present itself as an altered movement strategy on CMJ performance, rather than jump height assessment alone. Alongside the investigation of specific kinetic variables in monitoring NMF responses, the notion of start thresholds related to absolute and relative force changes needs further investigation. As noted by Gathercole, Sporer, Stellingwerff, et al. (2015a), it is important for practitioners to consider that some methods of assessment are often prone to false starts, with standardised jump initiation time perhaps being a better strategy to ensure reliability. Upon reviewing the findings of Gathercole, Sporer, Stellingwerff, et al. (2015a) it could therefore be concluded that a combined approach (outcome and strategy) to CMJ assessment, would perhaps provide more sensitivity in NMF detection, and the data provided would potentially display more information upon the athlete's preparedness for subsequent training.

Lastly, despite the focus of the experimental Chapter 7 being to detect time-course of recovery of CMJ and WB measures and not to detect NMF, it could be argued that the assessment of NMF is also warranted in future time-course of recovery research. From the literature review conducted, it is clear that assessment of time-course of recovery and NMF are two individually distinct processes and should therefore warrant separate testing protocols. It is, however, important for practitioners to note that the use of CMJ is questioned when assessing NMF in elite level rugby union, due to its lack of specificity. The match demands presented from prior research (Cunniffe et al., 2009; Cunningham et al., 2016; Jones et al., 2015; Quarrie et al., 2013) note large frequency of sprints, accelerations and decelerations, which it could be argued are more likely to be performed during match play than vertical jumping movements, therefore questioning the applicability of CMJ. Additional research questioning CMJ applicability is presented by Marrier et al. (2016), who indicated that the changes in CMJ performance were unaffected by a simulated rugby union sevens training session, while the 30 m sprint time increased in response to the prescribed training session. Marrier et al. (2016) therefore recommended the use of maximal sprints that measure force over a horizontal plane, as a more suitable assessment of NMF in rugby union, where these movements are more likely to occur in comparison to movements in the vertical plane. However, as previously explained (Chapter 2.4), the rationale and applicability of implementing maximal sprints in the days post-match which measure force over a horizontal plane, is perhaps unrealistic.

9.4.2 Application of subjective and objective measures of restoration

Alongside analysis of CMJ within this thesis, the assessment of WB scores in the days post-match also revealed results of interest for future practice. The finding that WB scores reduced to a greater value and for a longer time-course than CMJ is one of importance for future applications in elite settings. Despite evidence from this thesis supporting the use of both objective and subjective measures of monitoring athlete-training response, subjective measures were considered more sensitive in measuring fatigue. Further evidence for supporting the use of subjective measures was noted by Saw et al. (2016), who found in their systematic review that subjective measures reflected acute and chronic training loads with superior sensitivity and more consistency than objective measures. Practitioners are therefore advised to implement subjective measures within their testing battery. The reliability and sensitivity of WB scores identified within this thesis and their use alongside objective measures (specifically CMJ), in a mixed methods approach to monitoring restoration of performance in elite rugby union match play, is recommended. Additionally, when considering the large variability and financial expense associated with many objective measures of performance and the low financial expense associated with many subjective measures, the views of Saw et al. (2016) that subjective measures are a viable option for monitoring acute fatigue in the days post rugby union match play, is further supported. Based upon unpublished observations throughout the author's career in elite sport, it could also be argued that perhaps sometimes the best metric to monitor an athlete's readiness comes from asking players simple daily questions regarding their general well-being. However, in elite rugby environments, where squad sizes are large, the practicality of being able to speak to every player pre training session is unrealistic and therefore supports the continued use of self-report well-being questionnaires that players can complete in their own time, therefore limiting unrealistic practitioner responsibilities.

Future investigations assessing readiness on a daily basis within team sport settings will perhaps focus upon measures of performance derived from both objective and subjective testing. Recent research by Thorpe et al. (2015), assessing fatigue during a competitive phase of an elite soccer playing season, noted that perceived ratings of fatigue alongside rMSSD were sensitive to daily fluctuations in high intensity running. Despite the aforementioned limitations of using HR derived measures (Chapter 2.4.5) for assessing fatigue and the small correlation identified by Thorpe et al. (2015) between rMSSD and high intensity running, the results do show that vagal related time indices are a potential area of investigation for restoration of performance assessment in elite rugby union players. It is perhaps less surprising that moderate to strong correlations ($r = -0.51$, $p < 0.001$) were observed between the players perceived rating of fatigue and variations in high intensity running, with Thorpe et al. (2015) noting a 400 m increase in high intensity running leading to a 1 AU decrease in perceived fatigue. Results from this thesis, would therefore support the views of Thorpe et al. (2015), with WB scores recommended as an appropriate tool for non-invasive assessment of fatigue status in elite rugby union players. It should, however, be noted that WB application should be administered in a mixed methods approach to monitoring restoration of performance in elite rugby union match play.

9.4.3 Position-specific tests of performance restoration

As a result of this research it could be argued that, alongside individual data being assessed in comparison to mean values, the objective performance tests conducted should also be positional in focus. The content of these objective performance tests should perhaps be guided

by the match demands that individual positions are required to perform, with a restoration of performance test measuring the likely fatigue induced by these demands. The views of Gathercole, Sporer, Stellingwerff, et al. (2015a) support this notion, recommending a process of identification of variables that are subject to change in specific positions. It is likely that some strategy-focused variables are more sensitive to performance change than others, therefore potentially explaining the exclusion of some testing options.

Fatigue in positions such as full back and wing, which have been noted within this thesis to experience more accelerations than other positions (Chapter 3), may be better assessed by a performance test that measures a lower body explosive element. Positions that complete a large volume of accelerations and decelerations during match play, should perhaps have their NMF assessed by force at zero velocity, as this measure is likely to offer good repeatability and appears useful for inferring changes in movement strategy during the eccentric phase. Likewise, a prop and a full back have been shown (Chapter 3) to experience differing demands during game play and therefore the performance test that is conducted should perhaps reflect this. An additional consideration to support this notion, was the finding from this thesis that forwards experience a less reduced CMJ performance in the immediate days post-match compared to backs, despite experiencing a larger volume of high magnitude impacts during match play. One could therefore argue that implementing the use of a “plyometric push up” to assess position-specific upper body fatigue of forwards in the days post-match would be more appropriate. The above evidence, combined with unpublished observations from experimental Chapter 8 (showing forwards experiencing more ball carries, tackles and set piece collisions throughout game play than backs), mean it could be argued that the likely fatigue response of forwards is more related to upper body muscle soreness. It is therefore perhaps unsurprising within Chapter 7, that CMJ did not detect higher magnitude of fatigue in forwards compared to backs, as CMJ is aimed at assessing lower body mechanics and not upper body mechanics.

As previously explained, high magnitude impacts experienced via ball carries, tackles and set piece collisions, are thought to have a greater influence upon restoration of performance post-match. As such, the use of a “plyometric push up” in assessing upper body fatigue in future research may be a more reliable measure for use within assessment of forwards’ time-course of restoration. When considering this notion of a “plyometric push up” being used to assess upper body fatigue post-match, the use of the *OptoJump* should not be discounted, using the flight time calculation within the *OptoJump* software. This data assessing upper body fatigue could provide practitioners with a score upon which to make informed decisions upon forwards’ fatigue post-match. Evidence to support this notion was presented by Roe et al. (2015), who noted good reliability (CV < 5%) for “plyometric push up” assessed across flight time (2-3 repetitions), peak force (1 and repetitions) and mean force (1-3 repetitions). Lower reliability measures (CV > 5%) have previously been reported for “plyometric push up” (Hogarth, Deakin, & Sinclair, 2013) therefore supporting its use, yet the sub-elite level of the rugby league players within the study mean its relevance can be questioned. Perhaps most interesting from the research by Roe et al. (2015) was the finding that only mean force (2 and 3 repetitions) was capable of detecting SWC and this is something that would require consideration from practitioners looking to implement “plyometric push up” into their fatigue testing protocol. Flight time (2 and 3 repetitions), peak force (1 and 3 repetitions) and mean force (1-3 repetitions) all displayed a CV of <5%, therefore potentially discounting their use.

Lastly, in addition to the prescription of performance tests aligned with positional demands, the notion that performance tests should be prescribed based upon mechanical or metabolic elements is another area of future interest in this subject area. Prior research has identified the likely metabolic (Cummins, Gray, Shorter, Halaki, & Orr, 2016; Jones et al., 2014; Kempton, Sirotic, Rampinini, & Coutts, 2015; Lindsay, Lewis, Scarrott, Gill, et al., 2015; McLellan et al., 2011b; Twist & Highton, 2013) and mechanical fatigue (Coutts, Reaburn, Piva, & Murphy, 2007; Johnston et al., 2015; Johnston, Gabbett, et al., 2014; Johnston et al., 2013) induced by rugby match play, yet the mechanisms of effect associated with these responses are still unclear. It could be argued that positional groups experience either a predominate mechanical or metabolic fatigue as a result of match play and therefore the performance tests implemented should aim to investigate this response. Similarly, a positional group that experiences more impacts should perhaps have a performance test implemented that assesses elements of muscle soreness, as this is the likely response that would be assumed. It is, however, important for practitioners to note that prior to such position-specific performance testing being implemented, development of technology that would be able to test such measures needs to be reviewed.

9.4.4 Future GPS integration for recovery intervention

Based upon the results of this thesis, future implementation of GPS analysis in monitoring fatigue and the implementation of training interventions should encompass analysis of movement patterns and more specifically the way in which players encounter the impacts occurred during match play and training. As explained previously (Chapter 9.3.3), the way in which a player experiences an impact (collision or movement task) will have a major influence upon the resultant fatigue created, meaning that GPS analysis utilising impact metrics should involve the combined method approach detailed in Chapter 8. The evidence presented in Chapter 8 shows that GPS does not tell users all that they need to know regarding match demands, and in some cases can perhaps be misleading. In addition to a combined approach (GPS and video) being recommended, the use of relative GPS measures is proposed for future implementation. To the author's knowledge, no research has attempted to measure relative GPS metrics and resultant fatigue, yet the recent research by Delaney et al. (2016), illustrating considerably higher relative intensities ($150\text{--}180\text{ m}\cdot\text{min}^{-1}$) of match play compared to previous research in professional rugby union (Cahill et al., 2013; Lindsay, Draper, et al., 2015), signifies the need for relative measurement. Evidence supporting the use of relative measures is presented in the recent research by Delaney et al. (2016), who recommended the use of a rolling averages approach for intensity assessment, as their research showed the intensity of match play to be greater as the length of the moving average decreased ($ES=0.05\text{--}2.96$), thereby illustrating that whole match values may not be reflective of the most intense periods of match play. This evidence therefore highlights an inherent issue when considering intensity metrics and one that warrants the consideration of relative GPS metrics for practitioners, when comparing players and assessing resultant fatigue in future research. Future investigation needs to be aimed towards the way in which relative intensity ($\text{m}\cdot\text{min}$) during match play is performed for each position and in addition the resultant fatigue response created as a result of relative intensity. For example, one player could spend 40 minutes at $8\text{ km}\cdot\text{h}$ and 40 minutes at $4\text{ km}\cdot\text{h}$ and another could spend 40 minutes at $10\text{ km}\cdot\text{h}$ and 40 minutes at $2\text{ km}\cdot\text{h}$, therefore both equating to a total distance of 8 km and a relative intensity of $100\text{ m}\cdot\text{min}$. However, despite both these players achieving the same distances, the way in which they achieved this distance is different and therefore potentially does not present a clear picture of their match demands and likely fatigue created.

In addition to the future use of collision load (as discussed in Chapter 8.5), the use of software derived load metrics such as Dynamic Stress Load (DSL) and Metabolic Power (MP) used to assess the physiological cost of rugby union match play also need investigated further. Despite Delaney et al. (2016) noting MP values of 11-13.5 w/kg across varying positions and recommending assessment of this metric using a rolling averages approach, recent research (Hader, Mendez-Villanueva, Palazzi, Ahmaidi, & Buchheit, 2016) in highly trained soccer players questioned the use of MP as a measure of running load, when comparing changes of direction and straight line running. When considering that recent trends in GPS solutions have seen development of users' ability to track indices such as heart rate, impacts and stress loads instantaneously and report a value of "load" experienced, the reliability of the metrics and their associated algorithms needs to be critically appraised. DSL is used to assess the overall load of impacts, assessing magnitude of impacts and classifying the effect this has upon fatigue. However, similarly to collision load metrics, the use of DSL is yet to be validated and is a future area of investigation within match demands research.

Future research, incorporating impact assessments, should also perhaps involve an analysis of the exact points during match play at which collisions are most likely to occur. It could either be argued that the majority of impacts will occur at the start of the match, when players are fresh and therefore able to exert maximal intensity to impacts, or it could be argued that players are more likely to perform higher magnitude impacts in later parts of the match when fatigue is more common and opportunities to regain possession of the ball or halt attacking momentum are more prevalent. Information provided from an analysis of impact timings during match play, would perhaps help guide practitioners upon future training prescription, as the expected timing and magnitude of impacts during game play will be more fully understood. Secondly, analysis of rugby players in a laboratory setting, moving over force plates while wearing GPS units, would provide more detail around the impacts being generated during locomotion and the reliability of GPS unit impact classifications across zones. The findings of such an analysis of impact classifications zones, using the commonly reported "gold standard" force plate as a reference point against which to compare GPS, would better guide practitioners upon the relevance of GPS impact data within elite team sport settings.

Based upon the results from experimental Chapter 3 and 8, it can be assumed that accelerations and decelerations can be considered to account for a large and crucial element of elite rugby union match play. Another future GPS integration for assessing recovery intervention should then perhaps include the analysis of energetic costs of acceleration and deceleration tasks. Given the high energetic cost of accelerating and the tissue disruption associated with decelerating, the need for more research into the influence of these tasks upon resultant fatigue is warranted. Research assessing energy cost and metabolic power in elite soccer (Osgnach, Poser, Bernardini, Rinaldo, & Di Prampero, 2009) noted that instantaneous metabolic power can be calculated during match play, demonstrating that running speeds can generate different metabolic demands depending upon the acceleration incorporated. The research by Osgnach et al. (2009), therefore added to the knowledge of the influence of high intensity running (including accelerations and decelerations) upon fatigue, as the results showed that players covered 18% of their total distance $> 16 \text{ km/h}^{-1}$, yet this corresponded to 42% of the total energy being at high power ($> 20 \text{ w/kg}^{-1}$). More recently, however, this experimental approach was questioned by Buchheit, Manouvrier, Cassirame, and Morin (2015), with the application of this methodology utilising GPS noted to underestimate the energy demands of soccer specific drills, especially during recovery phases. The use of GPS in the calculation of energetic costs is

therefore questioned. Support for the use of metabolic power for the development of the understanding of the physical demands of team sport play, does, however, exist and has been noted by many authors (Castagna, Varley, Póvoas Araújo, & D'Ottavio, 2016; Coutts et al., 2015; Cummins et al., 2016; Kempton et al., 2015), yet to the author's knowledge no specific metabolic power research has been presented within rugby union. When considering the aforementioned poor reliability issues associated with short distance high-speed movements such as accelerations and decelerations, the use of GPS to assess these metrics and resultant fatigue can be questioned.

Lastly, when assessing impacts, it could perhaps be argued that impact zones should be individualised, as some players are likely to be able to tolerate larger impact forces than others. Future research should perhaps aim to incorporate the analysis of impact forces based upon prior research, showing what are considered "normal" for these positions. As a result of this analysis, comparing concurrent data against that of positional norms, a better understanding of the likely response impacts encountered during each match may have upon likely restoration of performance can be assumed. Additionally, future implementation of training programme prescription could be administered based upon longitudinal GPS data that assesses positional movement demands. When "eye balling" the results from Chapter 8, it was evident that no positional group appeared to display a pattern in the distribution of their changes of direction, accelerations or decelerations across impact zones. However, the implementation of longitudinal data collection, using GPS and video, may perhaps provide added detail upon the magnitude of changes of direction, accelerations or decelerations positions experienced across impact zones. This information would therefore help better guide practitioners upon the required conditioning components of positional groups. It is, however, important for practitioners to note that performance data, such as GPS or data derived from testing, should only be used as a guide and not an as element of performance coaching which is dictator driven. Based upon the results presented in the experimental chapters above and data previously reported (Buchheit, 2014; Buchheit et al., 2014), it could be argued that the important element for coaches is to assess athlete readiness in a holistic manner and make educated and informed decisions, which are guided by both data and "coaching art", whilst also ensuring they are non-emotional in nature.

9.4.5 Athletic resilience, training loads and hastened restoration of performance

Higher training loads were noted by Veugelers, Young, Fahrner, and Harvey (2015) to provide a protective effect against both injury and illness in elite Australian rules football, with this thesis also noting that recovery rates can be assumed as individual in nature, and can perhaps be guided by training load. A recently updated version of the aetiology model was recommended by Windt and Gabbett (2016), examining the influence of training loads upon injury. This notion of training load analysis and subsequent intervention is paramount for developing athletic resilience that can contribute to hastened restoration of performance. Similar research proposed by Hulin, Gabbett, Lawson, et al. (2016) investigating acute:chronic workload, also supports this view. Perhaps most importantly for practitioners working in elite rugby settings, were the findings by Hulin, Gabbett, Lawson, et al. (2016), that showed that players with a high chronic workload are more resilient to injury. A high chronic workload combined with a moderate (0.85-1.35) acute:chronic workload ratio was recommended by Hulin, Gabbett, Lawson, et al. (2016) to be appropriate for the development of injury resiliency.

Higher training loads have not always been recommended for improving rugby player resilience, with out-dated views by Gabbett & Jenkins (2011, p. 209) originally proposing "the

harder rugby league players train, the more injuries they will sustain". However, as knowledge has been developed in this topic area, the same authors are now in agreement that training load may actually assist in developing player resilience (Hulin, Gabbett, Caputi, Lawson, & Sampson, 2016; Hulin, Gabbett, Lawson, et al., 2016; Johnston et al., 2015). Similarly to the research by Hulin, Gabbett, Lawson, et al. (2016), a recent investigation assessing acute:chronic training loads in elite youth football players warrants attention. Bowen, Gross, Gimpel, and Li (2016) noted that accumulated workload and injury risk are related and that progressive increases in chronic workload may develop players' physical tolerance to acute loads. Malone, Roe, Doran, Gabbett, and Collins (2016b) also supported the notion that moderate increases in workload in Gaelic football appear to provide a protective measure against injury. These studies therefore further emphasise the view that increased levels of conditioning and appropriate load management may result in quicker recovery rates post rugby union match play and increased resilience to injury. Training load and readiness assessment are inextricably linked and when applying the above training load evidence to the findings from this thesis, performance testing using CMJ and WB should be implemented to regularly assess the effect training and playing is having upon elite rugby players' daily readiness.

The notion of training loads influencing the likelihood of injury is not a new phenomenon, yet as was presented by Gabbett (2016), the implementation of smarter training in place of harder training (using many of the methods critiqued and examined further in this thesis) are key for future improvements in this topic area. Perhaps the next level of investigation regarding the training load paradox, should involve the assessment of position-specific training load ratios. Based upon the results presented in thesis and the evidence critiqued previously, these position-specific training load ratios would not only help prevent avoidable injuries, but could also aid in the development of appropriate training load stimuli that would likely hasten restoration of performance time-course. Evidence to support this notion is presented by Murray et al. (2014), who showed that injury rates of specific playing positions are influenced by the amount of recovery between matches. The notions by Murray et al. (2014) therefore support the views of this thesis, in that match demands and specifically physical collisions have implications for future recovery programming.

The effect of players' physical condition and overall fitness levels on time-course of restoration also needs to be investigated. Killen et al. (2010) noted that maximal aerobic power acted as a protective measure for injury and this could perhaps mean that players with better overall fitness levels not only are protected from injury but also recover at quicker rates. These views were supported by recent research in Gaelic football by Malone et al. (2016b), recommending a high aerobic capacity to offer injury protection against rapid changes in workload. Similarly Johnston et al. (2015) noted that players with well developed high intensity running and lower body strength, were deemed as able to restore performance post-match play more quickly than players that did not display these attributes. If this evidence, supporting high fitness levels being a potential strategy to improve restoration of performance post-match, is believed to be consistent across elite rugby union settings, it could perhaps be argued that athletic resilience and improved fitness is the first obstacle for practitioners to overcome in their desire to improve player readiness between games.

Lastly, an additional point for consideration within the analysis of the results collated regarding changes of direction, acceleration and deceleration, is the notion that in a typical training week players are exposed to a larger frequency of changes of direction, acceleration and deceleration, than impacts. This exposure to changes of direction, acceleration and deceleration on a daily

basis, means that it could be argued that practitioners should only assess impacts from collisions, as these are the less regularly experienced demands and are likely to have a greater influence upon restoration. Adaptation and an ability to handle load experienced from changes of direction, acceleration and deceleration is potentially likely to occur naturally within training. Recently, this notion of appropriate exposure to maximal velocity events acting as a protective measure against injury was presented by Malone, Roe, Doran, Gabbett, and Collins (2016a) in elite Gaelic football players, yet evidence to specifically support this finding in elite level rugby union is still unfound. The focus of future recovery and restoration protocols using GPS impacts should therefore perhaps take more of a specific approach, to include quantification of impacts from collisions and not all impact instances. This notion could therefore form the basis of the rationale for excluding those impacts not experienced from collision, and would enable easier analysis and quantification of impacts occurred in relation to their likely effect upon restoration.

9.4.6 Physiological and psychological restoration post rugby union match play

It could be argued that all aspects of match output need to be recovered from, meaning recovery must therefore be individualised and should encompass both physical and mental restoration. One recent study of interest, is the work by Rattray et al. (2015) who proposed that modern post-exercise recovery strategies should focus upon not only peripheral mechanisms, but central mechanisms also. As demonstrated in this thesis, much of the attention of recovery strategies and their effectiveness has focused upon peripheral measures of fatigue, yet the views of Rattray et al. (2015) propose the notion that the assessment of central fatigue, alongside peripheral fatigue, is an important consideration for future practice. When considering the high cognitive load experienced by rugby union players, both in the build up to match play and during the match itself, the need to assess this psychological stressor and influence a hastening of restoration of performance from a central fatigue viewpoint is paramount. More focused future research upon the brain and its role in recovery post exercise is needed, with investigation into the recovery modalities that more effectively impact the central fatigue associated with the brain being key.

The ability of sports science practitioners to target central fatigue, as an intervention to improve restoration of performance following rugby union match play, would be a major advancement in the area of recovery. Further support for the implementation of central fatigue assessment and associated recovery, is noted when assessing the aforementioned research by Noakes (2012). When combining the views of Noakes (2012) (emphasising the role of central fatigue in performance decrement) with the notions of Rattray et al. (2015) (illustrating the importance of central fatigue within the recovery process), one could argue that central fatigue predetermines peripheral fatigue, so should perhaps be targeted initially to hasten the peripheral feelings of perceived fatigue. Future recovery intervention planning should therefore take into account elements of a rugby player's daily life, including, for example, peer pressure and potential pressure from sponsors. Practitioners working in the elite field are advised to look beyond physiological time-course of recovery assessment, and instead include a combined approach of physiological and psychosocial recovery intervention.

9.5 Final conclusion

A need for continued research in rugby union match demands exists, as the results presented regarding the applicability of GPS metrics in their current format are questionable. More accurate GPS load assessment metrics are required, with future technological developments in match demand assessment being recommended to include a combination of data taken from the GPS, accelerometer and gyroscope. Such software advances, combined with the use of the GPS and video analysis techniques applied within this thesis, could provide more detail in terms of the activities performed by positional groups and the likely resultant fatigue. As a result, a more meaningful analysis of match demands will be developed through better identification of movement. Relative measures are also recommended for involvement in future match demands research, as it could be argued that this thesis is perhaps more representative of modern rugby union than those conducted previously. Observations from this thesis would indicate that relative values for forwards are perhaps of more interest than those of the backs when assessing some variables, as they present more information from a relative rather than an absolute view. The notion of a relative position-specific assessment would better guide practitioners in future match demands analysis.

Other important findings from this thesis identified CMJ and WB as being applicable for use in restoration of performance testing, with a change in CMJ height of $\geq 1.7\%$ being meaningful and therefore warranting further investigation by practitioners. Despite CMJ height testing shown to be of use in elite rugby settings for assessing restoration of performance, WB assessment also indicated its worth. Results from this thesis would indicate that elite rugby players often do not restore performance prior to the next game commencing and that players often play in a sub-optimal state. The reduced CMJ performance and WB scores noted at 60 hours, 90 hours and 170 hours post rugby union match, between positional groups, is of importance for future training prescription in the immediate days post-match. Finally, results from this thesis would indicate that the differences in time-course of restoration between positional groups and reported for CMJ performance and WB scores, could be explained by both the match demands encountered and the typically accumulated training activities performed between games. When considering the number of fixtures in a season and the fact that match demands experienced by players are ever-increasing, the findings from this thesis are of prominence for many stakeholders within the elite game.

10 References

- Abaïdia, A.-E., Lamblin, J., Delecroix, B., Leduc, C., McCall, A., Nédélec, M., . . . Dupont, G. (2016). Recovery from exercise-induced muscle damage: Cold water immersion versus whole body cryotherapy. *International Journal of Sports Physiology and Performance*, *Published ahead of print*.
- Abbiss, C. R., & Laursen, P. B. (2005). Models to explain fatigue during prolonged endurance cycling. *Sports Med*, *35*(10), 865-898.
- Acero, R. M., Sanchez, J. A., & Fernandez-del-Olmo, M. (2012). Tests of vertical jump: Countermovement jump with arm swing and reaction jump with arm swing. *Strength and Conditioning Journal*, *34*(6), 87-93.
- Al Haddad, H., Parouty, J., & Buchheit, M. (2012). Effect of daily cold water immersion on heart rate variability and subjective ratings of well-being in highly trained swimmers. *International Journal of Sports Physiology and Performance*, *7*(1), 33-38.
- Alaphilippe, A., Mandigout, S., Ratel, S., Bonis, J., Courteix, D., & Duclos, M. (2012). Longitudinal follow-up of biochemical markers of fatigue throughout a sporting season in young elite rugby players. *Journal of Strength and Conditioning Research*, *26*(12), 3376-3384.
- Allman, B. L., & Rice, C. L. (2002). Neuromuscular fatigue and aging: Central and peripheral factors. *Muscle and Nerve*, *25*(6), 785-796.
- Andersen, L. L., Jay, K., Andersen, C. H., Jakobsen, M. D., Sundstrup, E., Topp, R., & Behm, D. G. (2013). Acute effects of massage or active exercise in relieving muscle soreness: Randomized controlled trial. *Journal of Strength and Conditioning Research*, *27*(12), 3352-3359.
- Appleby, B., Newton, R. U., & Cormie, P. (2012). Changes in strength over a 2-year period in professional rugby union players. *Journal of Strength and Conditioning Research*, *26*(9), 2538-2546.
- Aragon-Vargas, L. F. (2000). Evaluation of four vertical jump tests: Methodology, reliability, validity, and accuracy. [- 2000]. *Measurement In Physical Education and Exercise Science*, *4*(4), 215-228.
- Argus, C. K., Gill, N., Keogh, J., Hopkins, W. G., & Beaven, C. M. (2010). Effects of a short-term pre-season training programme on the body composition and anaerobic performance of professional rugby union players. *J Sports Sci*, *28*(6), 679-686.
- Argus, C. K., Gill, N., Keogh, J. W. L., McGuigan, M., & Hopkins, W. G. (2012). Effects of two contrast training programs on jump performance in rugby union players during a competition phase. *International Journal of Sports Physiology and Performance*, *7*(1), 68-75.
- Argus, C. K., Gill, N. D., & Keogh, J. W. L. (2012). Characterisation of the differences in strength and power between different levels of competition in rugby union athletes. *Journal of Strength and Conditioning Research*, *26*(10), 2698-2704.
- Argus, C. K., Gill, N. D., Keogh, J. W. L., & Hopkins, W. G. (2011). Assessing lower-body peak power in elite rugby-union players. *Journal of Strength and Conditioning Research*, *25*(6), 1616-1621.
- Argus, C. K., Gill, N. D., Keogh, J. W. L., Hopkins, W. G., & Beaven, C. M. (2009). Changes in strength, power, and steroid hormones during a professional rugby union competition. *Journal of Strength and Conditioning Research*, *23*(5), 1583-1592.
- Arteaga, R., Dorado, C., Chavarren, J., & Calbet, A. L. (2000). Reliability of jumping performance in active men and women under different stretch loading conditions. *Journal of Sports Medicine and Physical Fitness*, *40*(1), 26-34.
- Artero, E. G., Espana-Romero, V., Castro-Pinero, J., Ruiz, J. R., Jimenez-Pavon, D., Aparicio, V. A., . . . Ortega, F. B. (2012). Criterion-related validity of field-based muscular fitness tests in youth. *Journal of Sports Medicine and Physical Fitness*, *52*(3), 263-272.
- Asmussen, E. (1979). Muscle fatigue. *Med Sci Sports Exerc*, *11*(4), 313-321.
- Aubert, A. E., Seps, B., & Beckers, F. (2003). Heart rate variability in athletes. *Sports Med*, *33*(12), 889-919.

- Aubry, A., Hausswirth, C., Louis, J., Coutts, A. J., Buchheit, M., & Le Meur, Y. (2015). The development of functional overreaching is associated with a faster heart rate recovery in endurance athletes. *Plos One*, 10(10), e0139754.
- Austin, D. J., Gabbett, T. J., & Jenkins, D. G. (2011a). The physical demands of Super 14 rugby union. *Journal of Science and Medicine in Sport*, 14(3), 259-263.
- Austin, D. J., Gabbett, T. J., & Jenkins, D. G. (2013). Reliability and sensitivity of a repeated high-intensity exercise performance test for rugby league and rugby union. *Journal of Strength and Conditioning Research*, 27(4), 1128-1135.
- Austin, D. J., Gabbett, T. J., & Jenkins, D. J. (2011b). Repeated high-intensity exercise in a professional rugby league. *Journal of Strength and Conditioning Research*, 25(7), 1898-1904.
- Austin, D. J., & Kelly, S. J. (2013). Positional differences in professional rugby league match play through the use of global positioning systems. *Journal of Strength and Conditioning Research*, 27(1), 14-19.
- Bagger, M., Petersen, P. H., & Pedersen, P. K. (2003). Biological variation in variables associated with exercise training. *Int J Sports Med*, 24(6), 433-440.
- Baker, D. (1998). Applying the in-season periodization of strength and power training to football. *Strength and Conditioning*, 20(2), 18-24.
- Baker, D. (2001a). Comparison of upper-body strength and power between professional and college-aged rugby league players. *Journal of Strength and Conditioning Research*, 15(1), 30-35.
- Baker, D. (2001b). The effects of an in-season of concurrent training on the maintenance of maximal strength and power in professional and college-aged rugby league football players. *Journal of Strength and Conditioning Research*, 15(2), 172-177.
- Baker, D. (2001c). A series of studies on the training of high-intensity muscle power in rugby league football players. *Journal of Strength and Conditioning Research*, 15(2), 198-209.
- Baker, D. (2007). Cycle-length variants in periodized strength/power training. *Strength and Conditioning Journal*, 29(4), 10-17.
- Baker, J., Brown, E., Hill, G., Phillips, G., Williams, R., & Davies, B. (2002). Handgrip contribution to lactate production and leg power during high-intensity exercise. *Med Sci Sports Exerc*, 34(6), 1037-1040.
- Banfi, G., Lombardi, G., Colombini, A., & Melegati, G. (2010). Whole-body cryotherapy in athletes. *Sports Med*, 40(6), 509-517.
- Bangsbo, J., Iaia, F. M., & Krstrup, P. (2007). Metabolic response and fatigue in soccer. *International Journal of Sports Physiology and Performance*, 2(2), 111-127.
- Bangsbo, J., Iaia, F. M., & Krstrup, P. (2008). The Yo-Yo intermittent recovery test - A useful tool for evaluation of physical performance in intermittent sports. *Sports Med*, 38(1), 37-51.
- Bangso, J. (2000). Team sports. In R. J. Maughan (Ed.), *Nutrition in Sport* (pp. 574-587). Oxford: Blackwell Science Ltd.
- Banister, E. W. (1991). Modeling elite athletic performance. In J. D. MacDougall, H. A. Wenger & H. J. Green (Eds.), *Physiological Testing of the High- Performance Athlete* (pp. 403-424).
- Bar-Or, O., Dotan, R., & Inbar, O. (1977). A 30-second all-out ergometric test: its reliability and validity for anaerobic capacity. *Israel Journal of Medicine and Science*.
- Bara-Filho, M. G., Schimitz Freitas, D., Moreira, D., de Oliveira Matta, M., Roberto Perroux de Lima, J., & Nakamura, F. Y. (2013). Heart rate variability and soccer training: a case study. *Motriz, Rio Claro*, 19(1), 171-177.
- Barnes, M. J. (2014). Alcohol: Impact on sports performance and recovery in male athletes. *Sports Med*, 44(7), 909-919.
- Barnes, M. J., Mundel, T., & Stannard, S. R. (2012). The effects of acute alcohol consumption on recovery from a simulated rugby match. *J Sports Sci*, 30(3), 295-304.
- Barr, M. J., Sheppard, J. M., Agar-Newman, D. J., & Newton, R. U. (2014). Transfer effect of strength and power training to the sprinting kinematics of international rugby players. *The Journal of Strength and Conditioning Research*, 28(9), 2585-2596.

- Barrett, S., Midgley, A. W., Towlson, C., Garrett, A., Portas, M., & Lovell, R. (2016). Within-Match PlayerLoad™ Patterns During a Simulated Soccer Match: Potential Implications for Unit Positioning and Fatigue Management. [- 2016]. *International Journal of Sports Physiology & Performance*, 11(1), 135-140.
- Bazyler, C. D., Beckham, G. K., & Sato, K. (2015). The use of the isometric squat as a measure of strength and explosiveness. *Journal of Strength and Conditioning Research*, 29(5), 1386-1392.
- Beaven, C. M., Cook, C., Gray, D., Downes, P., Murphy, I., Drawer, S., . . . Gill, N. (2013). Electrostimulation's enhancement of recovery during a rugby preseason. *International Journal of Sports Physiology and Performance*, 8(1), 92-98.
- Beaven, C. M., Cook, C. J., & Gill, N. D. (2008). Significant strength gains observed in rugby players after specific resistance exercise protocols based on individual salivary testosterone responses. *Journal of Strength and Conditioning Research*, 22(2), 419-425.
- Beaven, C. M., Gill, N. D., & Cook, C. J. (2008). Salivary testosterone and cortisol responses in professional rugby players after four resistance exercise protocols. *Journal of Strength and Conditioning Research*, 22(2), 426-432.
- Bell, P. G., Walshe, I. H., Davison, G. W., Stevenson, E. J., & Howatson, G. (2015). Recovery facilitation with Montmorency cherries following high-intensity, metabolically challenging exercise. *Applied Physiology, Nutrition, and Metabolism*, 40(4), 414-423.
- Bell, W., Evans, W. D., Cobner, D. M., & Eston, R. G. (2005). The regional placement of bone mineral mass, fat mass, and lean soft tissue mass in young adult rugby union players. *Ergonomics*, 48(11-14), 1462-1472.
- Bellenger, C. R., Fuller, J. T., Thomson, R. L., Davison, K., Robertson, E. Y., & Buckley, J. D. (2016). Monitoring athletic training status through autonomic heart rate regulation: A systematic review and meta-analysis. *Sports Med*, 46(10), 1461-1486.
- Bevan, H. R., Owen, N. J., Cunningham, D. J., Kingsley, M. I. C., & Kilduff, L. P. (2009). Complex training in professional rugby players: Influence of recovery time on upper-body power output. *Journal of Strength and Conditioning Research*, 23(6), 1780-1785.
- Bleakley, C., McDonough, S., Gardner, E., Baxter, D. G., Hopkins, T. J., Davison, G. W., & Costa, M. T. (2012). Cold-water immersion (cryotherapy) for preventing and treating muscle soreness after exercise. *Sao Paulo Medical Journal*, 130(5), 348-348.
- Bleakley, C. M., Bieuzen, F., Davison, G. W., & Costello, J. T. (2014). Whole-body cryotherapy: Empirical evidence and theoretical perspectives. *Open Access Journal of Sports Medicine*, 5, 25-36.
- Bosco, C., Luhtanen, P., & Komi, P. V. (1983). A simple method for measurement of mechanical power in jumping. *European Journal of Applied Physiology and Occupational Physiology*, 50(2), 273-282.
- Bosco, C., Montanari, G., Ribacchi, R., Giovenali, P., Latteri, F., Iachelli, G., . . . Saibene, F. (1987). Relationship between the efficiency of muscular work during jumping and the energetics of running. *Eur J Appl Physiol*, 56(2), 138-143.
- Bosquet, L., Berryman, N., & Dupuy, O. (2009). A comparison of 2 optical timing systems designed to measure flight time and contact time during jumping and hopping. *Journal of Strength and Conditioning Research*, 23(9), 2660-2665.
- Bosquet, L., Merkari, S., Arvisais, D., & Aubert, A. E. (2008). Is heart rate a convenient tool to monitor over-reaching? A systematic review of the literature. *Br J Sports Med*, 42(9), 709-714.
- Boullosa, D. A., Tuimil, J. L., Alegre, L. M., Iglesias, E., & Lusquinos, F. (2011). Concurrent fatigue and potentiation in endurance athletes. *International Journal of Sports Physiology and Performance*, 6(1), 82-93.
- Bowen, L., Gross, A. S., Gimpel, M., & Li, F.-L. (2016). Accumulated workloads and the acute:chronic workload ratio relate to injury risk in elite youth football players. [2016/07/22]. *Br J Sports Med*, Published ahead of print.
- Bradley, W. J., Morehen, J. C., Haigh, J., Clarke, J., Donovan, T. F., Twist, C., . . . Close, G. L. (2016). Muscle glycogen utilisation during rugby match play: Effects of pre-game carbohydrate. *Journal of Science and Medicine in Sport*, 19(12), 1033-1038.

- Bruin, G., Kuipers, H., Keizer, H. A., & Vander Vusse, G. J. (1994). Adaptation and overtraining in horses subjected to increasing training loads. *J Appl Physiol* (1985), 76(5), 1908-1913.
- Buchheit, M. (2014). Monitoring training status with HR measures: do all roads lead to Rome? *Frontiers in Physiology*, 5, 73.
- Buchheit, M. (2016). The numbers will love you back in return—I promise. *International Journal of Sports Physiology and Performance*, 11(4), 551-554.
- Buchheit, M., Al Haddad, H., Simpson, B. M., Palazzi, D., Bourdon, P. C., Di Salvo, V., & Mendez-Villanueva, A. (2014). Monitoring accelerations with GPS in football: Time to slow down? *International Journal of Sports Physiology and Performance*, 9(3), 442-445.
- Buchheit, M., & Gindre, C. (2006). Cardiac parasympathetic regulation: respective associations with cardiorespiratory fitness and training load. *American Journal of Physiology-Heart and Circulatory Physiology*, 291(1), H451-H458.
- Buchheit, M., Lefebvre, B., Laursen, P., & Ahmaidi, S. (2011). Reliability, usefulness, and validity of the 30–15 intermittent ice test in young elite ice hockey players. *Journal of Strength and Conditioning Research*, 25(5), 1457-1464.
- Buchheit, M., Manouvrier, C., Cassirame, J., & Morin, J.-B. (2015). Monitoring locomotor load in soccer: Is metabolic power, powerful? *Int J Sports Med*, 36(14), 1149-1155.
- Buchheit, M., Millet, G. P., Parisy, A., Pourchez, S., Laursen, P. B., & Ahmaidi, S. (2008). Supramaximal training and postexercise parasympathetic reactivation in adolescents. *Med Sci Sports Exerc*, 40(2), 362-371.
- Buchheit, M., Papelier, Y., Laursen, P. B., & Ahmaidi, S. (2007). Noninvasive assessment of cardiac parasympathetic function: postexercise heart rate recovery or heart rate variability? *American Journal of Physiology-Heart and Circulatory Physiology*, 293(1), H8-H10.
- Buchheit, M., Racinais, S., Bilsborough, J. C., Bourdon, P. C., Voss, S. C., Hocking, J., . . . Coutts, A. J. (2013). Monitoring fitness, fatigue and running performance during a pre-season training camp in elite football players. *Journal of Science and Medicine in Sport*, 16(6), 550-555.
- Bunn, J. R., Canning, J., Burke, G., Mushipe, M., Marsh, D. R., & Li, G. (2004). Production of consistent crush lesions in murine quadriceps muscle - A biomechanical, histomorphological and immunohistochemical study. *Journal of Orthopaedic Research*, 22(6), 1336-1344.
- Byrne, C., & Eston, R. G. (2002). The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance. *J Sports Sci*, 20(5), 417-425.
- Byrne, C., Twist, C., & Eston, R. (2004). Neuromuscular function after exercise-induced muscle damage - Theoretical and applied implications. *Sports Med*, 34(1), 49-69.
- Cadore, E. L., Pinheiro, E., Izquierdo, M., Correa, C. S., Radaelli, R., Martins, J. B., . . . Pinto, R. S. (2013). Neuromuscular, hormonal, and metabolic responses to different plyometric training volumes in rugby players. *Journal of Strength and Conditioning Research*, 27(11), 3001-3010.
- Cahill, N., Lamb, K., Worsfold, P., Headey, R., & Murray, S. (2013). The movement characteristics of English Premiership rugby union players. *J Sports Sci*, 31(3), 229-237.
- Cairns, S. P., Knicker, A. J., Thompson, M. W., & Sjogaard, G. (2005). Evaluation of models used to study neuromuscular fatigue. *Exercise and Sport Sciences Reviews*, 33(1), 9-16.
- Calder, A. (2000). Recovery Training: advanced coaching study pack, Australian Sports Commission. Canberra.
- Calvert, T. W., Banister, E. W., Savage, M. V., & Bach, T. (1976). Systems model of effects of training on physical performance. *Ieee Transactions on Systems Man and Cybernetics*, 6(2), 94-102.
- Carlock, J. M., Smith, S. L., Hartman, M. J., Morris, R. T., Ciroslan, D. A., Pierce, K. C., . . . Stone, M. H. (2004). The relationship between vertical jump power estimates and weightlifting ability: A field-test approach. *Journal of Strength and Conditioning Research*, 18(3), 534-539.

- Casamichana, D., Castellano, J., Calleja-Gonzalez, J., San Roman, J., & Castagna, C. (2013). Relationship between indicators of training load in soccer players. *Journal of Strength and Conditioning Research*, 27(2), 369-374.
- Casartelli, N., Muller, R., & Maffiuletti, N. A. (2010). Validity and reliability of the Myotest accelerometric system for the assessment of vertical jump height. *Journal of Strength and Conditioning Research*, 24(11), 3186-3193.
- Casiero, D. (2013). Fueling the rugby player: Maximizing performance on and off the pitch. *Current Sports Medicine Reports*, 12(4), 228-233.
- Castagna, C., Ganzetti, M., Ditroilo, M., Giovannelli, M., Rocchetti, A., & Manzi, V. (2013). Concurrent validity of vertical jump performance assessment systems. *Journal of Strength and Conditioning Research*, 27(3), 761-768.
- Castagna, C., Varley, M., Póvoas Araújo, S. C., & D'Ottavio, S. (2016). The evaluation of the match external load in soccer: Methods comparison. [- 2016]. *International Journal of Sports Physiology and Performance*, Published ahead of print.
- Chambers, R., Gabbett, T. J., Cole, M. H., & Beard, A. (2015). The use of wearable microensors to quantify sport-specific movements. *Sports Med*, 45(7), 1065-1081.
- Chen, J.-L., Yeh, D.-P., Lee, J.-P., Chen, C.-Y., Huang, C.-Y., Lee, S.-D., . . . Kuo, C.-H. (2011). Parasympathetic nervous activity mirrors recovery status in weightlifting performance after training. *Journal of Strength and Conditioning Research*, 25(6), 1546-1552.
- Chiu, L. Z. F., & Barnes, J. L. (2003). The fitness-fatigue model revisited: Implications for planning short- and long-term training. *Strength and Conditioning Journal*, 25(6), 42-51.
- Choi, D., Cole, K. J., Goodpaster, B. H., Fink, W. J., & Costill, D. L. (1994). Effect of passive and active recovery on the resynthesis of muscle glycogen. *Med Sci Sports Exerc*, 26(8), 992-996.
- Clarke, A. C., Anson, J. M., & Pyne, D. B. (2017). Proof of concept of automated collision detection technology in rugby sevens. *The Journal of Strength and Conditioning Research*, Published ahead of print.
- Claudino, J. G., Cronin, J., Mezêncio, B., McMaster, D. T. W., McGuigan, M., Tricoli, V., . . . Serrão, J. C. (2016). The countermovement jump to monitor neuromuscular status: a meta-analysis. *Journal of Science and Medicine in Sport*, Published ahead of print.
- Coad, S., McLellan, C., Whitehouse, T., & Gray, B. (2015). Validity and reliability of a novel salivary immunoassay for individual profiling in applied sports science. *Research in Sports Medicine*, 23(2), 140-150.
- Cohen, J. (1988). *Statistical power analysis for the behavioural sciences* (2nd edition ed.). Hillside, N. J.: Lawrence Earlbaum Associates.
- Comfort, P., Haigh, A., & Matthews, M. J. (2012). Are changes in maximal squat strength during preseason training reflected in changes in sprint performance in rugby league players? *Journal of Strength and Conditioning Research*, 26(3), 772-776.
- Comfort, P., Jones, P. A., McMahon, J. J., & Newton, R. (2015). Effect of knee and trunk angle on kinetic variables during the isometric midthigh pull: Test-retest reliability. *International Journal of Sports Physiology and Performance*, 10(1), 58-63.
- Comfort, P., & McMahon, J. J. (2015). Reliability of maximal back squat and power clean performances in inexperienced athletes. *Journal of Strength and Conditioning Research*, 29(11), 3089-3096.
- Comyns, T., & Flanagan, E. P. (2013). Applications of the session rating of perceived exertion system in professional rugby union. *Strength and Conditioning Journal*, 35(6), 78-85.
- Comyns, T. M., Harrison, A. J., & Hennessy, L. K. (2010). Effect of squatting on sprinting performance and repeated exposure to complex training in male rugby players. *Journal of Strength and Conditioning Research*, 24(3), 610-618.
- Comyns, T. M., Harrison, A. J., Hennessy, L. K., & Jensen, R. L. (2007). Identifying the optimal resistive load for complex training in male rugby players. *Sports Biomechanics*, 6(1), 59-70.
- Cook, C., Kilduff, L., & Jones, M. R. (2014). Recovering effectively in high performance sports. In D. Joyce & D. Lewindon (Eds.), *High Performance Training for Sports*. Champaign: Human Kinetics.

- Cook, C. J., Kilduff, L. P., Crewther, B. T., Beaven, M., & West, D. J. (2014). Morning based strength training improves afternoon physical performance in rugby union players. *Journal of Science and Medicine in Sport*, 17(3), 317-321.
- Cormack, S. J., Monney, M. G., Morgan, W., & McGuigan, M. R. (2013). Influence of neuromuscular fatigue on accelerometer load in elite Australian football players. *International Journal of Sports Physiology and Performance*, 8(4), 373-378.
- Cormack, S. J., Newton, R. U., & McGuigan, M. R. (2008). Neuromuscular and Endocrine Responses of Elite Players to an Australian Rules Football Match. *International Journal of Sports Physiology and Performance*, 3(3), 359-374.
- Cormack, S. J., Newton, R. U., McGuigan, M. R., & Cormie, P. (2008). Neuromuscular and endocrine responses of elite players during an Australian rules football season. *International Journal of Sports Physiology and Performance*, 3(4), 439-453.
- Cormack, S. J., Newton, R. U., McGuigan, M. R., & Doyle, T. L. A. (2008). Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology and Performance*, 3(2), 131-144.
- Cormack, S. J., Smith, R. L., Mooney, M. M., Young, W. B., & O'Brien, B. J. (2014). Accelerometer load as a measure of activity profile in different standards of netball match play. *International Journal of Sports Physiology and Performance*, 9(2), 283-291.
- Cormie, P., McBride, J. M., & McCaulley, G. O. (2007). Validation of power measurement techniques in dynamic lower body resistance exercises. *Journal of Applied Biomechanics*, 23, 103-118.
- Cormie, P., McBride, J. M., & McCaulley, G. O. (2008). Power-time, force-time, and velocity-time curve analysis during the jump squat: Impact of load. *Journal of Applied Biomechanics*, 24(2), 112-120.
- Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *The Journal of Strength and Conditioning Research*, 23(1), 177-186.
- Cormie, P., McGuigan, M. R., & Newton, R. U. (2010a). Adaptations in athletic performance after ballistic power versus strength training. *Med Sci Sports Exerc*, 42(8), 1582-1598.
- Cormie, P., McGuigan, M. R., & Newton, R. U. (2010b). Influence of strength on magnitude and mechanisms of adaptation to power training. *Med Sci Sports Exerc*, 42(8), 1566-1581.
- Cornforth, D. J., Robinson, D. J., Spence, I., & Jelinek, H. F. (2014). Heart rate recovery in decision support for high performance athlete training schedules. *Interdisciplinary Journal of Information, Knowledge, and Management*, 9, 193-207.
- Cortina, J. M. (1993). What is coefficient alpha - an examination of theory and applications. *Journal of Applied Psychology*, 78(1), 98-104.
- Costello, J. T., Algar, L. A., & Donnelly, A. E. (2012). Effects of whole-body cryotherapy (-110 degrees C) on proprioception and indices of muscle damage. *Scandinavian Journal of Medicine & Science in Sports*, 22(2), 190-198.
- Costello, J. T., Baker, P. R. A., Minett, G. M., Bieuzen, F., B., S. I., & Bleakley, C. (2015). Whole-body cryotherapy (extreme cold air exposure) for preventing and treating muscle soreness after exercise in adults. *Cochrane Database of Systematic Reviews*, 9.
- Costill, D. L., Gollnick, P. D., Jansson, E. D., Saltin, B., & Stein, E. M. (1973). Glycogen depletion pattern in human muscle fibers during distance running. *Acta Physiologica Scandinavica*, 89(3), 374-383.
- Coughlan, G. F., Green, B. S., Pook, P. T., Toolan, E., & O'Connor, S. P. (2011). Physical game demands in elite rugby union: a global positioning system analysis and possible implications for rehabilitation. *Journal of Orthopaedic & Sports Physical Therapy*, 41(8), 600-605.
- Coutts, A., Reaburn, P., & Abt, G. (2003). Heart rate, blood lactate concentration and estimated energy expenditure in a semi-professional rugby league team during a match: a case study. *J Sports Sci*, 21(2), 97-103.
- Coutts, A., Reaburn, P., Piva, T. J., & Murphy, A. (2007). Changes in selected biochemical, muscular strength, power, and endurance measures during deliberate overreaching and tapering in rugby league players. *Int J Sports Med*, 28(2), 116-124.

- Coutts, A. J., & Duffield, R. (2010). Validity and reliability of GPS devices for measuring movement demands of team sports. *Journal of Science and Medicine in Sport*, 13(1), 133-135.
- Coutts, A. J., Kempton, T., Sullivan, C., Bilsborough, J. C., Cordy, J., & Rampinini, E. (2015). Metabolic power and energetic costs of professional Australian Football match-play. *Journal of Science and Medicine in Sport*, 18(2), 219-224.
- Coutts, A. J., Rampinini, E., Marcora, S. M., Castagna, C., & Impellizzeri, F. M. (2009). Heart rate and blood lactate correlates of perceived exertion during small-sided soccer games. *Journal of Science and Medicine in Sport*, 12(1), 79-84.
- Coutts, A. J., Reaburn, P., Piva, T. J., & Rowsell, G. J. (2007). Monitoring for overreaching in rugby league players. *Eur J Appl Physiol*, 99(3), 313-324.
- Coutts, A. J., Slattery, K. M., & Wallace, L. K. (2007). Practical tests for monitoring performance, fatigue and recovery in triathletes. *Journal of Science and Medicine in Sport*, 10(6), 372-381.
- Coutts, A. J., Wallace, L. K., & Slattery, K. M. (2007). Monitoring changes in performance, physiology, biochemistry, and psychology during overreaching and recovery in triathletes. *Int J Sports Med*, 28(2), 125-134.
- Cresswell, S. L., & Eklund, R. C. (2006). Changes in athlete burnout over a thirty-week "rugby year". *Journal of Science and Medicine in Sport*, 9(1-2), 125-134.
- Crewther, B. T., Lowe, T., Weatherby, R. P., Gill, N., & Keogh, J. (2009). Neuromuscular performance of elite rugby union players and relationships with salivary hormones. *Journal of Strength and Conditioning Research*, 23(7), 2046-2053.
- Crewther, B. T., Potts, N., Kilduff, L. P., Drawer, S., & Cook, C. J. (2017). Can salivary testosterone and cortisol reactivity to a mid-week stress test discriminate a match outcome during international rugby union competition? *Journal of Science and Medicine in Sport*, Published ahead of print.
- Crewther, B. T., Sanctuary, C. E., Kilduff, L. P., Carruthers, J. S., Gaviglio, C. M., & Cook, C. J. (2013). The workout responses of salivary-free testosterone and cortisol concentrations and their association with the subsequent competition outcomes in professional rugby league. *Journal of Strength and Conditioning Research*, 27(2), 471-476.
- Cross, M. J., Williams, S., Trewartha, G., Kemp, P. T., & Stokes, K. (2015). The influence of in-season training loads on injury risk in professional rugby union. *International Journal of Sports Physiology & Performance*, In Press.
- Cross, M. R., Brughelli, M., Brown, S. R., Samozino, P., Gill, N. D., Cronin, J. B., & Morin, J.-B. (2015). Mechanical properties of sprinting in elite rugby union and rugby league. *International Journal of Sports Physiology and Performance*, 10(6), 695-702.
- Crowcroft, S., McCleave, E., Slattery, K., & Coutts, A. J. (2016). Assessing the measurement sensitivity and diagnostic characteristics of athlete monitoring tools in national swimmers. *International Journal of Sports Physiology and Performance*, Published ahead of print.
- Crystal, N. J., Townson, D. H., Cook, S. B., & LaRoche, D. P. (2013). Effect of cryotherapy on muscle recovery and inflammation following a bout of damaging exercise. *Eur J Appl Physiol*, 113(10), 2577-2586.
- Cummins, C., Gray, A., Shorter, K., Halaki, M., & Orr, R. (2016). Energetic and metabolic power demands of national rugby league match-play. *Int J Sports Med*, 37(7), 552-558.
- Cummins, C., Orr, R., O'Connor, H., & West, C. (2013). Global positioning systems (GPS) and microtechnology sensors in team sports: A systematic review. *Sports Med*, 43(10), 1025-1042.
- Cunniffe, B., Hore, A. J., Whitcombe, D. M., Jones, K. P., Baker, J. S., & Davies, B. (2010). Time course of changes in immunoendocrine markers following an international rugby game. *Eur J Appl Physiol*, 108(1), 113-122.
- Cunniffe, B., Proctor, W., Baker, J. S., & Davies, B. (2009). An evaluation of the physiological demands of elite rugby union using global positioning system tracking software. *Journal of Strength and Conditioning Research*, 23(4), 1195-1203.

- Cunningham, D., Shearer, D. A., Drawer, S., Eager, R., Taylor, N., Cook, C., & Kilduff, L. P. (2016). Movement demands of elite U20 international rugby union players. *Plos One*, 11(4), e0153275.
- Cunningham, D. J., West, D. J., Owen, N. J., Shearer, D. A., Finn, C. V., Bracken, R. M., . . . Kilduff, L. P. (2013). Strength and power predictors of sprinting performance in professional rugby players. *Journal of Sports Medicine and Physical Fitness*, 53(2), 105-111.
- Daanen, H. A. M., Lamberts, R. P., Kallen, V. L., Jin, A. M., & Van Meeteren, N. L. U. (2012). A systematic review on heart-rate recovery to monitor changes in training status in athletes. *International Journal of Sports Physiology and Performance*, 7(3), 251-260.
- Dabbs, J. M. (1990). Salivary testosterone measurements - reliability across hours, days, and weeks. *Physiology & Behavior*, 48(1), 83-86.
- Damas, F., Nosaka, K., Libardi, C. A., Chen, T. C., & Ugrinowitsch, C. (2016). Susceptibility to exercise-induced muscle damage: A cluster analysis with a large sample. *Int J Sports Med*, 37(8), 633-640.
- Darrall-Jones, J. D., Jones, B., & Till, K. (2015). Anthropometric and physical profiles of english academy rugby union players. *Journal of Strength and Conditioning Research*, 29(8), 2086-2096.
- Darrall-Jones, J. D., Jones, B., Till, K., & Roe, G. (2015). Reliability and usefulness of linear sprint testing in adolescent rugby union and league players. *Journal of Strength and Conditioning Research*, 30(5), 1359-1364.
- Davies, V., Thompson, K. G., & Cooper, S.-M. (2009). The effects of compression garments on recovery. *Journal of Strength and Conditioning Research*, 23(6), 1786-1794.
- Dawson, B., Gow, S., Modra, S., Bishop, D., & Stewart, G. (2005). Effects of immediate post-game recovery procedures on muscle soreness, power and flexibility levels over the next 48 hours. *Journal of Science and Medicine in Sport*, 8(2), 210-221.
- De Pauw, K., Roelands, B., Marusic, U., Tellez, H. F., Knaepen, K., & Meeusen, R. (2013). Brain mapping after prolonged cycling and during recovery in the heat. *J Appl Physiol* (1985), 115(9), 1324-1331.
- Delaney, J. A., Thornton, H. R., Pryor, J. F., Stewart, A. M., Dascombe, B. J., & Duthie, G. M. (2016). Peak running intensity of international rugby: Implications for training prescription. [-2016]. *International Journal of Sports Physiology and Performance*, Published ahead of print.
- Derman, W., Schwellnus, M. P., Lambert, M. I., Emms, M., SinclairSmith, C., Kirby, P., & Noakes, T. D. (1997). The 'worn-out athlete': A clinical approach to chronic fatigue in athletes. *J Sports Sci*, 15(3), 341-351.
- Deutsch, M. U., Kearney, G. A., & Rehrer, N. J. (2007). Time - motion analysis of professional rugby union players during match-play. *J Sports Sci*, 25(4), 461-472.
- Deutsch, M. U., Maw, G. J., Jenkins, D., & Reaburn, P. (1998). Heart rate, blood lactate and kinematic data of elite colts (under-19) rugby union players during competition. *J Sports Sci*, 16(6), 561-570.
- Di Salvo, V., Collins, A., McNeill, B., & Cardinale, M. (2006). Validation of Prozone ®: A new video-based performance analysis system. *International Journal of Performance Analysis in Sport*, 6(1), 108-119.
- Dobson, B. P., & Keogh, J. W. L. (2007). Methodological issues for the application of time-motion analysis research. *Strength and Conditioning Journal*, 29(2), 48-55.
- Docherty, D., Wenger, H. A., & Neary, P. (1988). Time-motion analysis related to the physiological demands of rugby. *Journal of Human Movement Studies*, 14(6), 269-277.
- Dodd, S., Powers, S. K., Callender, T., & Brooks, E. (1984). Blood lactate disappearance at various intensities of recovery exercise. *J Appl Physiol* (1985), 57(5), 1462-1465.
- Dogramaci, S. N., Watsford, M. L., & Murphy, A. J. (2011). The reliability and validity of subjective notational analysis in comparison to global positioning system tracking to assess athlete movement patterns. *Journal of Strength and Conditioning Research*, 25(3), 852-859.
- Domire, Z. J., & Challis, J. H. (2007). The influence of squat depth on maximal vertical jump performance. *J Sports Sci*, 25(2), 193-200.

- Driller, M. W., Argus, C. K., Bartram, J. C., Bonaventura, J., Martin, D. T., West, N. P., & Halson, S. L. (2014). Reliability of a 2-bout exercise test on a wattbike cycle ergometer. *International Journal of Sports Physiology and Performance*, 9(2), 340-345.
- Driller, M. W., Argus, C. K., & Shing, C. M. (2012). The Reliability of a 30 Second Sprint Test on the Wattbike Cycle Ergometer. *International Journal of Sports Physiology and Performance*, 8(4), 379-383.
- Duffield, R., Edge, J., Merrells, R., Hawke, E., Barnes, M., Simcock, D., & Gill, N. (2008). The effects of compression garments on intermittent exercise performance and recovery on consecutive days. *International Journal of Sports Physiology and Performance*, 3(4), 454-468.
- Duffield, R., Murphy, A., Snape, A., Minett, G. M., & Skein, M. (2012). Post-match changes in neuromuscular function and the relationship to match demands in amateur rugby league matches. *Journal of Science and Medicine in Sport*, 15(3), 238-243.
- Duthie, G., Pyne, D., & Hooper, S. (2003a). Applied physiology and game analysis of rugby union. *Sports Med*, 33(13), 973-991.
- Duthie, G., Pyne, D., & Hooper, S. (2003b). The reliability of video based time motion analysis. *Journal of Human Movement Studies*, 44(3), 259-271.
- Duthie, G. M., Pyne, D. B., Marsh, D. J., & Hooper, S. L. (2006). Sprint patterns in rugby union players during competition. *Journal of Strength and Conditioning Research*, 20(1), 208-214.
- Eagles, A., McLellan, C., Hing, W., Carloss, N., & Lovell, D. (2014). Changes in sleep quantity and efficiency in professional rugby union players during home based training and match-play. *Journal of Sports Medicine and Physical Fitness*, 56(5), 565-571.
- Ebben, W. P., Flanagan, E. P., & Jensen, R. L. (2007). Gender similarities in rate of force development and time to takeoff during the countermovement jump. *Journal of Exercise Physiology Online*, 10(6), 10-17.
- Edmonds, R. C., Sinclair, W. H., & Leicht, A. S. (2013). Effect of a training week on heart rate variability in elite youth rugby league players. *Int J Sports Med*, 34(12), 1087-1092.
- Edwards, R. H. T. (1983). Biochemistry of exercise. In K. H. G. & V. J. A. (Eds.), *Biochemistry of exercise* (pp. 1-28). Champaign, IL: Human Kinetics.
- Edwards, R. H. T., Hill, D. K., Jones, D. A., & Merton, P. A. (1977). Fatigue of long duration in human skeletal-muscle after exercise. *Journal of Physiology*, 272(3), 769-778.
- Elloumi, M., Maso, F., Michaux, O., Robert, A., & Lac, G. (2003). Behaviour of saliva cortisol C , testosterone T and the T/C ratio during a rugby match and during the post-competition recovery days. *Eur J Appl Physiol*, 90(1-2), 23-28.
- Elloumi, M., Maso, F., Robert, A., Michaux, O., & Lac, G. (2003). Saliva cortisol and testosterone values during the week following a match in rugbymen. *Science & Sports*, 18(3), 164-165.
- Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: what, why and how it influences muscle function. *The Journal of Physiology*, 586(1), 11-23.
- Fairchild, T. J., Armstrong, A. A., Rao, A., Liu, H., Lawrence, S., & Fournier, P. A. (2003). Glycogen synthesis in muscle fibers during active recovery from intense exercise. *Med Sci Sports Exerc*, 35(4), 595-602.
- Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, 41(4), 1149-1160.
- Ferreira, L. C., Schilling, B. K., Weiss, L. W., Fry, A. C., & Chiu, L. Z. (2010). Reach height and jump displacement: Implications for standardization of reach determination. *Journal of Strength and Conditioning Research*, 24(6), 1596-1601.
- Filaire, E., Bernain, X., Sagnol, M., & Lac, G. (2001). Preliminary results on mood state, salivary testosterone:cortisol ratio and team performance in a professional soccer team. *Eur J Appl Physiol*, 86(2), 179-184.
- Filaire, E., Lac, G., & Pequignot, J. M. (2003). Biological, hormonal, and psychological parameters in professional soccer players throughout a competitive season. *Perceptual and Motor Skills*, 97(3), 1061-1072.

- Filaire, E., Legrand, B., Lac, G., & Pequignot, J. M. (2004). Training of elite cyclists: effects on mood state and selected hormonal responses. *J Sports Sci*, 22(11-12), 1025-1033.
- Flanagan, E. P., Ebben, W. P., & Jensen, R. L. (2008). Reliability of the reactive strength index and time to stabilization during depth jumps. *Journal of Strength and Conditioning Research*, 22(5), 1677-1682.
- Flatt, A. A., & Esco, M. R. (2013). Validity of the ithlete (TM) smart phone application for determining ultra-short-term heart rate variability. *Journal of Human Kinetics*, 39(1), 85-92.
- Flatt, A. A., & Esco, M. R. (2015). Evaluating individual training adaptation with Smartphone-derived heart rate variability in a collegiate female soccer team. *The Journal of Strength and Conditioning Research*, 30(2), 378-385.
- Fomin, R., Grainger, A., Nasedkin, V., Bork, A., & Huttunen, P. (2015). *Training process optimization based on game success prediction in English professional rugby union*. Paper presented at the 20th Annual Congress of the European College of Sports Science, Malmo, Sweden.
- Fomin, R., & Nasedkin, V. (2013). *Effective management of athlete preparation: A comprehensive approach to monitoring the athlete's individual readiness [White paper]*
- Fontana, F. Y., Colosio, A. L., Da Lozzo, G., & Pogliaghi, S. (2016). Player's success prediction in rugby union: From youth performance to senior level placing. *Journal of Science and Medicine in Sport*, Published ahead of print.
- Foster, C., Hector, L. L., Welsh, R., Schrager, M., Green, M. A., & Snyder, A. C. (1995). Effects of specific versus cross-training on running performance. *European Journal of Applied Physiology and Occupational Physiology*, 70(4), 367-372.
- Fowles, J. R. (2006). Technical issues in quantifying low-frequency fatigue in athletes. *International Journal of Sports Physiology and Performance*, 1(2), 169-171.
- French, D. N., Gomez, A. L., Volek, J. S., Rubin, M. R., Ratamess, N. A., Sharman, M. J., . . . Kraemer, W. J. (2004). Longitudinal tracking of muscular power changes of NCAA Division I collegiate women gymnasts. *Journal of Strength and Conditioning Research*, 18(1), 101-107.
- Fullagar, H. H. K., Skorski, S., Duffield, R., Hammes, D., Coutts, A. J., & Meyer, T. (2015). Sleep and athletic performance: the effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. *Sports Med*, 45(2), 161-186.
- Fuller, C. W., Brooks, J. H. M., Cancea, R. J., Hall, J., & Kemp, S. P. T. (2007). Contact events in rugby union and their propensity to cause injury. *Br J Sports Med*, 41(12), 862-867.
- Gabbett, T. J. (2013). Quantifying the physical demands of collision sports: Does microsensor technology measure what it claims to measure? *Journal of Strength and Conditioning Research*, 27(8), 2319-2322.
- Gabbett, T. J. (2016). The training—injury prevention paradox: should athletes be training smarter and harder? *Br J Sports Med*, 50(5), 273-280.
- Gabbett, T. J., Jenkins, D., & Abernethy, B. (2010). Physical collisions and injury during professional rugby league skills training. *Journal of Science and Medicine in Sport*, 13(6), 578-583.
- Gabbett, T. J., & Jenkins, D. G. (2011). Relationship between training load and injury in professional rugby league players. *Journal of Science and Medicine in Sport*, 14(3), 204-209.
- Gabbett, T. J., Jenkins, D. G., & Abernethy, B. (2011). Physical collisions and injury in professional rugby league match-play. *Journal of Science and Medicine in Sport*, 14(3), 210-215.
- Gabbett, T. J., Kelly, J. N., & Sheppard, J. M. (2008). Speed, change of direction speed, and reactive agility of rugby league players. *Journal of Strength and Conditioning Research*, 22(1), 174-181.
- Gaitanos, G. C., Williams, C., Boobis, L. H., & Brooks, S. (1993). Human muscle metabolism during intermittent maximal exercise. *J Appl Physiol* (1985), 75(2), 712-719.
- Gallardo-Fuentes, F., Gallardo-Fuentes, J., Ramirez-Camillo, R., Balsalobree-Fernandez, C., Martinez, C., Caniuqueo, A., . . . Izquierdo, M. (2016). Inter and intra-session reliability

- and validity of the MyJump app for measuring different jump actions in trained male and female athletes. *The Journal of Strength and Conditioning Research*, 30(7), 2049–2056.
- Galliera, E., Dogliotti, G., Melegati, G., Romanelli, M., Cabitza, P., & Banfi, G. (2013). Bone remodelling biomarkers after whole body cryotherapy (WBC) in elite rugby players. *Injury-International Journal of the Care of the Injured*, 44(8), 1117-1121.
- Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews*, 81(4), 1725-1789.
- Gannon, E., Stokes, K., & Trewartha, G. (2015). Strength and power development in professional rugby union players over a training and playing season. *International Journal of Sports Physiology and Performance*, 11(3), 381-387.
- Garcia-Lopez, J., Peleteiro, J., Rodriguez-Marroyo, J. A., Morante, J. C., Herrero, J. A., & Villa, J. G. (2005). The validation of a new method that measures contact and flight times during vertical jump. *Int J Sports Med*, 26(4), 294-302.
- Garland, S. J., & Gossen, E. R. (2002). The muscular wisdom hypothesis in human muscle fatigue. *Exercise and Sport Sciences Reviews*, 30(1), 45-49.
- Gastin, P. B., McLean, O., Spittle, M., & Breed, R. V. P. (2013). Quantification of tackling demands in professional Australian football using integrated wearable athlete tracking technology. *Journal of Science and Medicine in Sport*, 16(6), 689-593.
- Gastin, P. B., Meyer, D., & Robinson, D. (2013). Perceptions of wellness to monitor adaptive responses to training and competition in elite australian football. *Journal of Strength and Conditioning Research*, 27(9), 2518-2526.
- Gastmann, U., Petersen, K. G., Bocker, J., & Lehmann, M. (1998). Monitoring intensive endurance training at moderate energetic demands using resting laboratory markers failed to recognize an early overtraining stage. *Journal of Sports Medicine and Physical Fitness*, 38(3), 188-193.
- Gathercole, R., Sporer, B., & Stellingwerff, T. (2015). Countermovement jump performance with increased training loads in elite female rugby athletes. *Int J Sports Med*, 36(9), 722-728.
- Gathercole, R., Sporer, B., Stellingwerff, T., & Sleivert, G. (2015a). Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. *International Journal of Sports Physiology and Performance*, 10(1), 84-92.
- Gathercole, R. J., Sporer, B. C., Stellingwerff, T., & Sleivert, G. G. (2015b). Comparison of the capacity of different jump and sprint field tests to detect neuromuscular fatigue. *The Journal of Strength and Conditioning Research*, 29(9), 2522-2531.
- Gathercole, R. J., Stellingwerff, T., & Sporer, B. (2015). Effect of acute fatigue and training adaptation on countermovement jump performance in elite snowboard cross athletes. *Journal of Strength and Conditioning Research*, 29(1), 37-46.
- Gaviglio, C. M., & Cook, C. J. (2014). Relationship between midweek training measures of testosterone and cortisol concentrations and game outcome in professional rugby union matches. *Journal of Strength and Conditioning Research*, 28(12), 3447-3452.
- Gee, T. I., French, D. N., Howatson, G., Payton, S. J., Berger, N. J., & Thompson, K. G. (2011). Does a bout of strength training affect 2,000 m rowing ergometer performance and rowing-specific maximal power 24 h later? *Eur J Appl Physiol*, 111(11), 2653-2662.
- George, T. M., Olsen, P. D., Kimber, N. E., Shearman, J. P., Hamilton, J. G., & Hamlin, M. J. (2015). The effect of altitude and travel on rugby union performance: Analysis of the 2012 Super Rugby competition. *Journal of Strength and Conditioning Research*, 29(12), 3360-3366.
- Gill, N. D., Beaven, C. M., & Cook, C. (2006). Effectiveness of post-match recovery strategies in rugby players. *Br J Sports Med*, 40(3), 260-263.
- Glatthorn, J. F., Gouge, S., Nussbaumer, S., Stauffacher, S., Impellizzeri, F. M., & Maffiuletti, N. A. (2011). Validity and reliability of optojump photoelectric cells for estimating vertical jump height. *Journal of Strength and Conditioning Research*, 25(2), 556-560.
- Gollnick, P. D., Bayly, W. M., & Hodgson, D. R. (1986). Exercise intensity, training, diet, and lactate concentration in muscle and blood. *Med Sci Sports Exerc*, 18(3), 334-340.

- Gomez-Piriz, P. T., Jimenez-Reyes, P., & Ruiz-Ruiz, C. (2011). Relation between total body load and session rating of perceived exertion in professional soccer players. *Journal of Strength and Conditioning Research*, 25(8), 2100-2103.
- Gonzalez-Bono, E., Salvador, A., Serrano, M. A., & Ricarte, J. (1999). Testosterone, cortisol, and mood in a sports team competition. *Hormones and Behavior*, 35(1), 55-62.
- Green, B. S., Blake, C., & Caulfield, B. M. (2011). A comparison of cutting technique performance in rugby union players. *Journal of Strength and Conditioning Research*, 25(10), 2668-2680.
- Greig, M. (2008). The influence of soccer-specific fatigue on peak isokinetic torque production of the knee flexors and extensors. *The American journal of sports medicine*, 36(7), 1403-1409.
- Grove, J. R., & Prapavessis, H. (1992). Preliminary evidence for the reliability and validity of an abbreviated profile of mood states. *International Journal of Sport Psychology*, 23(2), 93-109.
- Hader, K., Mendez-Villanueva, A., Palazzi, D., Ahmaidi, S., & Buchheit, M. (2016). Metabolic power requirement of change of direction speed in young soccer players: Not all is what it seems. *Plos One*, 11(3), e0149839.
- Haff, G. G., & Nimphius, S. (2012). Training principles for power. *Strength and Conditioning Journal*, 34(6), 2-12.
- Haff, G. G., Ruben, R. P., Lider, J., Twine, C., & Cormie, P. (2015). A comparison of methods for determining the rate of force development during isometric midthigh clean pulls. *Journal of Strength and Conditioning Research*, 29(2), 386-395.
- Haff, G. G., Stone, M., Obryant, H. S., Harman, E., Dinan, C., Johnson, R., & Han, K. H. (1997). Force-time dependent characteristics of dynamic and isometric muscle actions. *Journal of Strength and Conditioning Research*, 11(4), 269-272.
- Haff, G. G., & Stone, M. H. (2015). Methods of developing power with special reference to football players. *Strength and Conditioning Journal*, 37(6), 2-16.
- Haff, G. G., Whitley, A., & Potteiger, J. A. (2001). A brief review: Explosive exercises and sports performance. *Strength and Conditioning Journal*, 23(3), 13-20.
- Halsen, S. L. (2008). Nutrition, sleep and recovery. *European Journal of Sport Science*, 8(2), 119-126.
- Halsen, S. L. (2014). Monitoring training load to understand fatigue in athletes. *Sports Med*, 44(2), S139-S147.
- Halsen, S. L., Bridge, M. W., Meeusen, R., Busschaert, B., Gleeson, M., Jones, D. A., & Jeukendrup, A. E. (2002). Time course of performance changes and fatigue markers during intensified training in trained cyclists. *J Appl Physiol* (1985), 93(3), 947-956.
- Halsen, S. L., & Jeukendrup, A. E. (2004). Does overtraining exist? An analysis of overreaching and overtraining research. *Sports Med*, 34(14), 967-981.
- Halsen, S. L., Lancaster, G. I., Jeukendrup, A. E., & Gleeson, M. (2003). Immunological responses to overreaching in cyclists. *Med Sci Sports Exerc*, 35(5), 854-861.
- Hamilton, D. (2009). Drop jumps as an indicator of neuromuscular fatigue and recovery in elite youth soccer athletes following tournament match play. *Journal of Australian Strength and Conditioning*, 17(4), 3-8.
- Hamlin, M. J., Mitchell, C. J., Ward, F. D., Draper, N., Shearman, J. P., & Kimber, N. E. (2012). Effect of compression garments on short-term recovery of repeated sprint and 3-km running performance in rugby union players. *Journal of Strength and Conditioning Research*, 26(11), 2975-2982.
- Harman, E. A., Rosenstein, M. T., Frykman, P. N., & Rosenstein, R. M. (1990). The effects of arms and countermovement on vertical jumping. *Med Sci Sports Exerc*, 22(6), 825-833.
- Harris, N. K., Cronin, J. B., Hopkins, W. G., & Hansen, K. T. (2008). Squat jump training at maximal power loads vs. heavy loads: Effect on sprint ability. *Journal of Strength and Conditioning Research*, 22(6), 1742-1749.
- Harrison, A. J., & Bourke, G. (2009). The effect of resisted sprint training on speed and strength performance in male rugby players. *Journal of Strength and Conditioning Research*, 23(1), 275-283.

- Harrison, A. J., & Gaffney, S. D. (2004). Effects of muscle damage on stretch-shortening cycle function and muscle stiffness control. *Journal of Strength and Conditioning Research*, 18(4), 771-776.
- Hartwig, T. B., Naughton, G., & Searl, J. (2009). Load, stress, and recovery in adolescent rugby union players during a competitive season. *J Sports Sci*, 27(10), 1087-1094.
- Hatze, H. (1998). Validity and reliability of methods for testing vertical jumping performance. *Journal of Applied Biomechanics*, 14(2), 127-140.
- Hausler, J., Halaki, M., & Orr, R. (2016). Application of global positioning system and microsensor technology in competitive rugby league match-play: A systematic review and meta-analysis. *Sports Med*, 46(4), 559-588.
- Hausswirth, C., Louis, J., Bieuzen, F., Pournot, H., Fournier, J., Filliard, J.-R., & Brisswalter, J. (2011). Effects of whole-body cryotherapy vs. Far-infrared vs. Passive modalities on recovery from exercise-induced muscle damage in highly-trained runners. *Plos One*, 6(12), e27749.
- Hayes, L. D., Sculthorpe, N., Young, J. D., Baker, J. S., & Grace, F. M. (2014). Critical difference applied to exercise-induced salivary testosterone and cortisol using enzyme-linked immunosorbent assay (ELISA): distinguishing biological from statistical change. *Journal of Physiology and Biochemistry*, 70(4), 991-996.
- Healy, R., Kenny, I. C., & Harrison, A. J. (2016). Assessing reactive strength measures in jumping and hopping using the OptoJump™ system. *Journal of Human Kinetics*, 54(1), 23-32.
- Hedelin, R., Kentta, G., Wiklund, U., Bjerle, P., & Henriksson-Larsen, K. (2000). Short-term overtraining: effects on performance, circulatory responses, and heart rate variability. *Med Sci Sports Exerc*, 32(8), 1480-1484.
- Hellard, P., Avalos, M., Lacoste, L., Barale, F., Chatard, J. C., & Millet, G. P. (2006). Assessing the limitations of the Banister model in monitoring training. *J Sports Sci*, 24(5), 509-520.
- Hemmings, B., Smith, M., Graydon, J., & Dyson, R. (2000). Effects of massage on physiological restoration, perceived recovery, and repeated sports performance. *Br J Sports Med*, 34(2), 109-114.
- Herman, K., Barton, C., Malliaras, P., & Morrissey, D. (2012). The effectiveness of neuromuscular warm-up strategies, that require no additional equipment, for preventing lower limb injuries during sports participation: a systematic review. *Bmc Medicine*, 10(1), 75.
- Higgins, T. R., Heazlewood, I. T., & Climstein, M. (2011). A random control trial of contrast baths and ice baths for recovery during competition in u/20 rugby union. *Journal of Strength and Conditioning Research*, 25(4), 1046-1051.
- Highton, J., Mullen, T., Norris, J., Oxendale, C., & Twist, C. (2016). Energy expenditure derived from micro-technology is not suitable for assessing internal load in collision-based activities. *International Journal of Sports Physiology and Performance*, Published ahead of print.
- Hill, A. V. (1914). The oxidative removal of lactic acid. *Journal of Physiology*, 48(6).
- Hill, J., Howatson, G., van Someren, K., Leeder, J., & Pedlar, C. (2014). Compression garments and recovery from exercise-induced muscle damage: a meta-analysis. *Br J Sports Med*, 48(18), 1340-1346.
- Hoffman, J. R., Kang, J., Ratamess, N. A., & Faigenbaum, A. D. (2005). Biochemical and hormonal responses during an intercollegiate football season. *Med Sci Sports Exerc*, 37(7), 1237-1241.
- Hoffman, J. R., Maresh, C. M., Newton, R. U., Rubin, M. R., French, D. N., Volek, J. S., . . . Kraemer, W. J. (2002). Performance, biochemical, and endocrine changes during a competitive football game. *Med Sci Sports Exerc*, 34(11), 1845-1853.
- Hoffman, J. R., Ratamess, N. A., & Kang, J. (2011). Performance changes during a college playing career in ncaa division iii football athletes. *Journal of Strength and Conditioning Research*, 25(9), 2351-2357.
- Hogarth, L., Deakin, G., & Sinclair, W. (2013). Are plyometric push-ups a reliable power assessment tool? *Journal of Australian Strength and Conditioning*, 21(1), 67-69.
- Holway, F. E., & Spriet, L. L. (2011). Sport-specific nutrition: Practical strategies for team sports. *J Sports Sci*, 29(1), S115-S125.

- Hongsuwan, C., Eungpinichpong, W., Chatchawan, U., & Yamauchi, J. (2015). Effects of Thai massage on physical fitness in soccer players. *Journal of Physical Therapy Science*, 27(2), 505-508.
- Hooper, S. L., & Mackinnon, L. T. (1995). Monitoring overtraining in athletes - recommendations. *Sports Med*, 20(5), 321-327.
- Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Med*, 30(1), 1-15.
- Hopkins, W. G. (2004). How to interpret changes in an athletic performance test. [- 2004]. *Sportscience*, 8(1), 1-7.
- Hopkins, W. G., Schabert, E. J., & Hawley, J. A. (2012). Reliability of power in physical performance tests. *Sports Med*, 31(3), 211-234.
- Hori, N., Newton, R., Kawamori, N., McGuigan, M., Kraemer, W. J., & Kazunori, N. (2009). Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. [- 2009]. *Journal of Strength and Conditioning Research*, 23(3), 872-884.
- Hori, N., Newton, R. U., Andrews, W. A., Kawamori, N., McGuigan, M. R., & Nosaka, K. (2008). Does performance of hang power clean differentiate performance of jumping, sprinting, and changing of direction? *Journal of Strength and Conditioning Research*, 22(2), 412-418.
- Howarth, K. R., Moreau, N. A., Phillips, S. M., & Gibala, M. J. (2009). Coingestion of protein with carbohydrate during recovery from endurance exercise stimulates skeletal muscle protein synthesis in humans. *J Appl Physiol* (1985), 106(4), 1394-1402.
- Howatson, G., Brandon, R., & Hunter, A. M. (2016). The response to, and recovery from maximum strength and power training in elite track and field athletes. *International Journal of Sports Physiology and Performance*, 11(3), 356-362.
- Howatson, G., McHugh, M. P., Hill, J. A., Brouner, J., Jewell, A. P., van Someren, K. A., . . . Howatson, S. A. (2010). Influence of tart cherry juice on indices of recovery following marathon running. *Scandinavian Journal of Medicine & Science in Sports*, 20(6), 843-852.
- Hulin, B. T., Gabbett, T. J., Caputi, P., Lawson, D. W., & Sampson, J. A. (2016). Low chronic workload and the acute: chronic workload ratio are more predictive of injury than between-match recovery time: a two-season prospective cohort study in elite rugby league players. *Br J Sports Med*, 50(16), 1008-1012.
- Hulin, B. T., Gabbett, T. J., Lawson, D. W., Caputi, P., & Sampson, J. A. (2016). The acute:chronic workload ratio predicts injury: high chronic workload may decrease injury risk in elite rugby league players. *Br J Sports Med*, 50(4).
- Hunkin, S. L., Fahrner, B., & Gatin, P. B. (2014). Creatine kinase and its relationship with match performance in elite Australian Rules football. *Journal of Science and Medicine in Sport*, 17(3), 332-336.
- Iellamo, F., Pigozzi, F., Spataro, A., Lucini, D., & Pagani, M. (2004). T-wave and heart rate variability changes to assess training in world-class athletes. *Med Sci Sports Exerc*, 36(8), 1342-1346.
- Impellizzeri, F. M., Rampinini, E., Coutts, A. J., Sassi, A., & Marcora, S. M. (2004). Use of RPE-based training load in soccer. *Med Sci Sports Exerc*, 36(6), 1042-1047.
- Jacobs, I., Westlin, N., Karlsson, J., Rasmussen, M., & Houghton, B. (1982). Muscle glycogen and diet in elite soccer players. *Eur J Appl Physiol*, 48(3), 297-302.
- Jakeman, J. R., Byrne, C., & Eston, R. G. (2010). Lower limb compression garment improves recovery from exercise-induced muscle damage in young, active females. *Eur J Appl Physiol*, 109(6), 1137-1144.
- Jardine, M. A., Wiggins, T. M., Myburgh, K. H., & Noakes, T. D. (1988). Physiological characteristics of rugby players including muscle glycogen content and muscle fibre composition. *South African Medical Journal*, 73(9), 529-532.
- Jennings, C. L., Viljoen, W., Durandt, J., & Lambert, M. I. (2005). The reliability of the FitroDyne as a measure of muscle power. *Journal of Strength and Conditioning Research*, 19(4), 859-863.

- Jennings, D., Cormack, S., Coutts, A. J., Boyd, L., & Aughey, R. J. (2010). The validity and reliability of GPS units for measuring distance in team sport specific running patterns. *International Journal of Sports Physiology and Performance*, 5(3), 328-341.
- Jensen, R. L., Furlong, L.-A. M., Graham, D., & Harrison, A. J. (2011). Reliability of jump and performance measures in rugby union players. *Portuguese Journal of Sports Sciences*, 11(2), 93-96.
- Jentjens, R., & Jeukendrup, A. E. (2003). Determinants of post-exercise glycogen synthesis during short-term recovery. *Sports Med*, 33(2), 117-144.
- Jidovtseff, B., Harris, N. K., Crielaard, J.-M., & Cronin, J. B. (2011). Using the load-velocity relationship for 1rm prediction. *Journal of Strength and Conditioning Research*, 25(1), 267-270.
- Johnston, R. D., & Gabbett, T. J. (2011). Repeated-sprint and effort ability in rugby league players. *Journal of Strength and Conditioning Research*, 25(10), 2789-2795.
- Johnston, R. D., Gabbett, T. J., Jenkins, D. G., & Hulin, B. T. (2015). Influence of physical qualities on post-match fatigue in rugby league players. *Journal of Science and Medicine in Sport*, 18(2), 209-213.
- Johnston, R. D., Gabbett, T. J., Seibold, A. J., & Jenkins, D. G. (2014). Influence of physical contact on neuromuscular fatigue and markers of muscle damage following small-sided games. *Journal of Science and Medicine in Sport*, 17(5), 535-540.
- Johnston, R. D., Gibson, N. V., Twist, C., Gabbett, T. J., Macnay, S. A., & Macfarlane, N. G. (2013). Physiological responses to an intensified period of rugby league competition. *Journal of Strength and Conditioning Research*, 27(3), 643-654.
- Johnston, R. J., Watsford, M. L., Kelly, S. J., Pine, M. J., & Spurrs, R. W. (2014). Validity and interunit reliability of 10 hz and 15 Hz GPS units for assessing athlete movement demands. *Journal of Strength and Conditioning Research*, 28(6), 1649-1655.
- Jones, A. M. (2014). Influence of dietary nitrate on the physiological determinants of exercise performance: a critical review. *Applied Physiology Nutrition and Metabolism*, 39(9), 1019-1028.
- Jones, D. A. (1996). High and low-frequency fatigue revisited. *Acta Physiologica Scandinavica*, 156(3), 270.
- Jones, M. R., West, D. J., Crewther, B. T., Cook, C. J., & Kilduff, L. P. (2015). Quantifying positional and temporal movement patterns in professional rugby union using global positioning system. *European Journal of Sport Science*, 15(6), 488-496.
- Jones, M. R., West, D. J., Harrington, B. J., Cook, C. J., Bracken, R. M., Shearer, D. A., & Kilduff, L. P. (2014). Match play performance characteristics that predict post-match creatine kinase responses in professional rugby union players. *BMC Sports Science, Medicine and Rehabilitation*, 6(1), 1-7.
- Jones, T. W., Smith, A., Macnaughton, L. S., & French, D. N. (2017). Variances in strength and conditioning practice in elite rugby union between the northern and southern hemispheres. *The Journal of Strength and Conditioning Research*, Published ahead of print.
- Jonhagen, S., Ackermann, P., Eriksson, T., Saartok, T., & Renstrom, P. (2004). Sports massage after eccentric exercise. *The American journal of sports medicine*, 32(6), 1499-1503.
- Kamandulis, S., Skurvydas, A., Snieckus, A., Masiulis, N., Aagaard, P., Dargeviciute, G., & Brazaitis, M. (2011). Monitoring markers of muscle damage during a 3 week periodized drop-jump exercise programme. *J Sports Sci*, 29(4), 345-353.
- Kawamori, N., & Haff, G. G. (2004). The optimal training load for the development of muscular power. *Journal of Strength and Conditioning Research*, 18(3), 675-684.
- Keller, U., Szinnai, G., Bilz, S., & Berneis, K. (2003). Effects of changes in hydration on protein, glucose and lipid metabolism in man: impact on health. *European Journal of Clinical Nutrition*, 57, S69-S74.
- Kellmann, M. (2002). *Enhancing Recovery: preventing underperformance in athletes*. Champaign, IL: Human Kinetics.

- Kelly, D., Coughlan, G. F., Green, B. S., & Caulfield, B. M. (2012). Automatic detection of collisions in elite level rugby union using a wearable sensing device. *Sports Engineering*, 15(2), 81-92.
- Kempton, T., Sirotic, A. C., Cameron, M., & Coutts, A. J. (2013). Match-related fatigue reduces physical and technical performance during elite rugby league match-play: a case study. *J Sports Sci*, 31(16), 1770-1780.
- Kempton, T., Sirotic, A. C., Rampinini, E., & Coutts, A. J. (2015). Metabolic power demands of rugby league match play. *International Journal of Sports Physiology and Performance*, 10(1), 23-28.
- Kennedy, R., & Drake, D. (2017a). The effect of acute fatigue on countermovement jump performance in rugby union players during preseason training. [- 2015]. *J Sports Sci*, 33, s44-s59.
- Kennedy, R. A., & Drake, D. (2017b). Dissociated time course of recovery between strength and power after isoinertial resistance loading in rugby union players. [- 2017]. *The Journal of Strength and Conditioning Research*.
- Kent-Braun, J. A. (1999). Central and peripheral contributions to muscle fatigue in humans during sustained maximal effort. *European Journal of Applied Physiology and Occupational Physiology*, 80(1), 57-63.
- Kent-Braun, J. A., Miller, R. G., & Weiner, M. W. (1993). Phases of metabolism during progressive exercise to fatigue in human skeletal-muscle. *J Appl Physiol* (1985), 75(2), 573-580.
- Kentta, G., & Hassinen, P. (1998). Overtraining and recovery - A conceptual model. *Sports Med*, 26(1), 1-16.
- Kilduff, L. P., Bevan, H. R., Kingsley, M. I. C., Owen, N. J., Bennett, M. A., Bunce, P. J., . . . Cunningham, D. J. (2007). Postactivation potentiation in professional rugby players: Optimal recovery. *Journal of Strength and Conditioning Research*, 21(4), 1134-1138.
- Killen, N. M., Gabbett, T. J., & Jenkins, D. G. (2010). Training loads and incidence of injury during the preseason in professional rugby league players. *Journal of Strength and Conditioning Research*, 24(8), 2079-2084.
- Killer, S. C., Svendsen, I. S., Jeukendrup, A. E., & Gleeson, M. (2015). Evidence of disturbed sleep and mood state in well-trained athletes during short-term intensified training with and without a high carbohydrate intervention. *J Sports Sci*, 1-9.
- King, T., Jenkins, D., & Gabbett, T. (2009). A time-motion analysis of professional rugby league match-play. [- 2009/02/01]. *J Sports Sci*, 27(3), 213-219.
- Kinugasa, T., & Kilding, A. E. (2009). A comparison of post-match recovery strategies in youth soccer players. *Journal of Strength and Conditioning Research*, 23(5), 1402-1407.
- Kirkpatrick, J., & Comfort, P. (2013). Strength, power, and speed qualities in English junior elite rugby league players. *The Journal of Strength and Conditioning Research*, 27(9), 2414-2419.
- Klavora, P. (2000). Vertical-jump tests: A critical review. *Strength and Conditioning Journal*, 22(5), 70-75.
- Klimek, A. T., Lubkowska, A., Szygula, Z., Chudecka, M., & Fraczek, B. (2010). Influence of the ten sessions of the whole body cryostimulation on aerobic and anaerobic capacity. *International Journal of Occupational Medicine and Environmental Health*, 23(2), 181-189.
- Knicker, A. J., Renshaw, I., Oldham, A. R. H., & Cairns, S. P. (2011). Interactive processes link the multiple symptoms of fatigue in sport competition. *Sports Med*, 41(4), 307-328.
- Kölling, S., Steinacker, J. M., Endler, S., Ferrauti, A., Meyer, T., & Kellmann, M. (2016). The longer the better: Sleep-wake patterns during preparation of the World Rowing Junior Championships. *Chronobiology International*, 33(1), 73-84.
- Kraemer, W. J., Fry, A. C., Rubin, M. R., Triplett-McBride, T., Gordon, S. E., Koziris, L. P., . . . Fleck, S. J. (2001). Physiological and performance responses to tournament wrestling. *Med Sci Sports Exerc*, 33(8), 1367-1378.
- Kraemer, W. J., & Ratamess, N. A. (2005). Hormonal responses and adaptations to resistance exercise and training. *Sports Med*, 35(4), 339-361.

- Kreider, R. B., O'Toole, M. L., Fry, A. C., Kibler, W. B., Nieman, D. C., Whelan, J. P., & Lehmann, M. (1998). Overtraining in sport. *Med Sci Sports Exerc*, 30(5), S225-S225.
- Krustrup, P., Mohr, M., Steensberg, A., Bencke, J., Kjaer, M., & Bangsbo, J. (2006). Muscle and blood metabolites during a soccer game: Implications for sprint performance. *Med Sci Sports Exerc*, 38(6), 1165-1174.
- Krustrup, P., Zeris, M., Jensen, J. M., & Mohr, M. (2010). Game-induced fatigue patterns in elite female soccer. *Journal of Strength and Conditioning Research*, 24(2), 427-441.
- Kuipers, H., & Keizer, H. A. (1988). Overtraining in elite athletes - review and directions for the future. *Sports Med*, 6(2), 79-92.
- Kuzmits, F. E., & Adams, A. J. (2008). The NFL combine: Does it predict performance in the national football league? *Journal of Strength and Conditioning Research*, 22(6), 1721-1727.
- La Torre, A., Castagna, C., Gervasoni, E., Ce, E., Rampichini, S., Ferrarin, M., & Merati, G. (2010). Acute effects of static stretching on squat jump performance at different knee starting angles. *Journal of Strength and Conditioning Research*, 24(3), 687-694.
- Lacome, M., Piscione, J., Hager, J.-P., & Carling, C. (2015). Analysis of running and technical performance in substitute players in international male rugby union competition. *International Journal of Sports Physiology and Performance*, 11(6), 783-792.
- Lamberts, R. P., Swart, J., Capostagno, B., Noakes, T. D., & Lambert, M. I. (2010). Heart rate recovery as a guide to monitor fatigue and predict changes in performance parameters. *Scandinavian Journal of Medicine & Science in Sports*, 20(3), 449-457.
- Lamberts, R. P., Swart, J., Noakes, T. D., & Lambert, M. I. (2009). Changes in heart rate recovery after high-intensity training in well-trained cyclists. *Eur J Appl Physiol*, 105(5), 705-713.
- Lamberts, R. P., Swart, J., Noakes, T. D., & Lambert, M. I. (2011). A novel submaximal cycle test to monitor fatigue and predict cycling performance. *Br J Sports Med*, 45(10), 797-804.
- Laux, P., Krumm, B., Diers, M., & Flor, H. (2015). Recovery-stress balance and injury risk in professional football players: a prospective study. *J Sports Sci*, 33(20), 2140-2148.
- Le Meur, Y., Buchheit, M., Aubry, A., Coutts, A. J., & Hausswirth, C. (2016). Assessing overreaching with HRR: What is the minimal exercise intensity required? *International Journal of Sports Physiology and Performance*, Published ahead of print.
- Le Meur, Y., Pichon, A., Schaal, K., Schmitt, L., Louis, J., Gueneron, J., . . . Hausswirth, C. (2013). Evidence of parasympathetic hyperactivity in functionally overreached athletes. *Med Sci Sports Exerc*, 45(11), 2061-2071.
- Leard, J. S., Cirillo, M. A., Katsnelson, E., Kimiatek, D. A., Miller, T. W., Trebincevic, K., & Garbalosa, J. C. (2007). Validity of two alternative systems for measuring vertical jump height. *Journal of Strength and Conditioning Research*, 21(4), 1296-1299.
- Leeder, J., Gissane, C., van Someren, K., Gregson, W., & Howatson, G. (2012). Cold water immersion and recovery from strenuous exercise: a meta-analysis. *Br J Sports Med*, 46(4), 233-240.
- Leeder, J., Glaister, M., Pizzoferrero, K., Dawson, J., & Pedlar, C. (2012). Sleep duration and quality in elite athletes measured using wristwatch actigraphy. *J Sports Sci*, 30(6), 541-545.
- Lees, A., Vanrenterghem, J., & De Clercq, D. (2004). Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics*, 37(12), 1929-1940.
- Lees, A., Vanrenterghem, J., & De Clercq, D. (2006). The energetics and benefit of an arm swing in submaximal and maximal vertical jump performance. *J Sports Sci*, 24(1), 51-57.
- Leti, T., & Bricout, V. A. (2013). Interest of analyses of heart rate variability in the prevention of fatigue states in senior runners. *Autonomic Neuroscience-Basic & Clinical*, 173(1-2), 14-21.
- Lewis, N. A., Collins, D., Pedlar, C. R., & Rogers, J. P. (2015). Can clinicians and scientists explain and prevent unexplained underperformance syndrome in elite athletes: an interdisciplinary perspective and 2016 update. *BMJ Open Sport Exerc Med*, 1(1), e000063.
- Lindsay, A., & Costello, J. T. (2016). Realising the potential of urine and saliva as diagnostic tools in sport and exercise medicine. *Sports Med*, 47(1), 11-31.

- Lindsay, A., Draper, N., Lewis, J., Gieseg, S. P., & Gill, N. (2015). Positional demands of professional rugby. *European Journal of Sport Science*, 15(6), 480-487.
- Lindsay, A., Lewis, J., Gill, N., Gieseg, S. P., & Draper, N. (2015). Effect of varied recovery interventions on markers of psychophysiological stress in professional rugby union. *European Journal of Sport Science*, 15(6), 543-549.
- Lindsay, A., Lewis, J., Scarrott, C., Draper, N., & Gieseg, S. P. (2015). Changes in acute biochemical markers of inflammatory and structural stress in rugby union. *J Sports Sci*, 33(9), 882-891.
- Lindsay, A., Lewis, J. G., Scarrott, C., Gill, N., Gieseg, S. P., & Draper, N. (2015). Assessing the effectiveness of selected biomarkers in the acute and cumulative physiological stress response in professional rugby union through non-invasive assessment. *Int J Sports Med*, 36(6), 446-454.
- Lombard, W. P., Durandt, J. J., Masimla, H., Green, M., & Lambert, M. I. (2015). Changes in body size and physical characteristics of South African under-20 rugby union players over a 13-year period. *Journal of Strength and Conditioning Research*, 29(4), 980-988.
- Lovell, T. W. J., Sirotic, A. C., Impellizzeri, F. M., & Coutts, A. J. (2013). Factors affecting perception of effort (session rating of perceived exertion) during rugby league training. *International Journal of Sports Physiology and Performance*, 10(7), 62-69.
- Lum, D., Landers, G., & Peeling, P. (2010). Effects of a recovery swim on subsequent running performance. *Int J Sports Med*, 31(1), 26-30.
- Lund, H., Vestergaard-Poulsen, P., Kanstrup, I. L., & Sejrnsen, P. (1998). The effect of passive stretching on delayed onset muscle soreness, and other detrimental effects following eccentric exercise. *Scandinavian Journal of Medicine & Science in Sports*, 8(4), 216-221.
- Macnaughton, L. S., Wardle, S. L., Witard, O. C., McGlory, C., Hamilton, D. L., Jeromson, S., . . . Tipton, K. D. (2016). The response of muscle protein synthesis following whole-body resistance exercise is greater following 40 g than 20 g of ingested whey protein. *Physiological Reports*, 4(15), e12893.
- Malone, J. J., Di Michele, R., Morgans, R., Burgess, D., Morton, J. P., & Drust, B. (2015). Seasonal training-load quantification in elite english premier league soccer players. *International Journal of Sports Physiology and Performance*, 10(4), 489-497.
- Malone, S., Roe, M., Doran, D. A., Gabbett, T. J., & Collins, K. (2016a). High chronic training loads and exposure to bouts of maximal velocity running reduce injury risk in elite Gaelic football. *Journal of Science and Medicine in Sport*, Published ahead of print.
- Malone, S., Roe, M., Doran, D. A., Gabbett, T. J., & Collins, K. D. (2016b). Aerobic fitness and playing experience protect against spikes in workload: The role of the acute: chronic workload ratio on injury risk in elite gaelic football. *International Journal of Sports Physiology and Performance*, Published ahead of print.
- Mann, T. (2007). Sporting myths : the real role of lactate during exercise : commentary. *South African Journal of Sports Medicine*, 19(5), 114-116.
- Mann, T. N., Lamberts, R. P., & Lambert, M. I. (2014). High responders and low responders: Factors associated with individual variation in response to standardized training. *Sports Med*, 44(8), 1113-1124.
- Marcora, S. M., Bosio, A., & de Morree, H. M. (2008). Locomotor muscle fatigue increases cardiorespiratory responses and reduces performance during intense cycling exercise independently from metabolic stress. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, 294(3), R874-R883.
- Marcora, S. M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans. *J Appl Physiol* (1985), 106(3), 857-864.
- Markovic, G., Dizdar, D., Jukic, I., & Cardinale, M. (2004). Reliability and factorial validity of squat and countermovement jump tests. *Journal of Strength and Conditioning Research*, 18(3), 551-555.
- Marques, M. C., Izquierdo, M., van den Tillaar, R., Moir, G. L., Sánchez-Medina, L., & González-Badillo, J. J. (2014). The reliability of force-time variables recorded during vertical jump performance and their relationship with jump height in power trained athletes. [-2014]. *International Sportmed Journal*, 15(2), 146-155.

- Marqués-Jiménez, D., Calleja-González, J., Arratibel, I., Delextrat, A., & Terrados, N. (2016). Are compression garments effective for the recovery of exercise-induced muscle damage? A systematic review with meta-analysis. *Physiology & Behavior*, 153, 133-148.
- Marrier, B., Le Meur, Y., Robineau, J., Lacombe, M., Couderc, A., Hausswirth, C., . . . Morin, J.-B. (2016). Quantifying neuromuscular fatigue induced by an intense training session in rugby sevens. *International Journal of Sports Physiology and Performance*, Published ahead of print.
- Mashiko, T., Umeda, T., Nakaji, S., & Sugawara, K. (2004a). Position related analysis of the appearance of and relationship between post-match physical and mental fatigue in university rugby football players. *Br J Sports Med*, 38(5), 617-621.
- Mashiko, T., Umeda, T., Nakaji, S., & Sugawara, K. (2004b). Position related analysis of the appearance of and relationship between post-match physical and mental fatigue in university rugby football players. *Br J Sports Med*, 38(5), 617-621.
- Maso, F., Lac, G., Filaire, E., Michaux, O., & Robert, A. (2004). Salivary testosterone and cortisol in rugby players: correlation with psychological overtraining items. *Br J Sports Med*, 38(3), 260-263.
- Maughan, R. J., & Shirreffs, S. M. (2010). Dehydration and rehydration in competitive sport. *Scandinavian Journal of Medicine & Science in Sports*, 20(3), 40-47.
- Mazzeo, R. S., Brooks, G. A., Schoeller, D. A., & Budinger, T. F. (1986). Disposal of blood [1-13C] lactate in humans during rest and exercise. *J Appl Physiol* (1985), 60(1), 232-241.
- McArdle, B., Katch, F. I., & Katch, V. L. (2005). *Essentials of exercise physiology*. Philadelphia, PA: Lippincott, Williams and Wilkins.
- McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (1999). A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *Journal of Strength and Conditioning Research*, 13(1), 58-66.
- McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (2002). The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. *Journal of Strength and Conditioning Research*, 16(1), 75-82.
- McCall, A., Nedelec, M., Carling, C., Le Gall, F., Berthoin, S., & Dupont, G. (2015). Reliability and sensitivity of a simple isometric posterior lower limb muscle test in professional football players. *J Sports Sci*, 33(12), 1298-1304.
- McLean, B. D., Coutts, A. J., Kelly, V., McGuigan, M. R., & Cormack, S. J. (2010). Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. *International Journal of Sports Physiology and Performance*, 5(3), 367-383.
- McLellan, C. P., & Lovell, D. I. (2012). Neuromuscular responses to impact and collision during elite rugby league match play. *Journal of Strength and Conditioning Research*, 26(5), 1431-1440.
- McLellan, C. P., Lovell, D. I., & Gass, G. C. (2010). Creatine kinase and endocrine responses of elite players pre, during, and post rugby league match play. *Journal of Strength and Conditioning Research*, 24(11), 2908-2919.
- McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011a). Biochemical and endocrine responses to impact and collision during elite rugby league match play. *Journal of Strength and Conditioning Research*, 25(6), 1553-1562.
- McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011b). Markers of postmatch fatigue in professional rugby league players. *Journal of Strength and Conditioning Research*, 25(4), 1030-1039.
- McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011c). Performance analysis of elite rugby league match play using global positioning systems. *Journal of Strength and Conditioning Research*, 25(6), 1703-1710.
- McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011d). The role of rate of force development on vertical jump performance. *Journal of Strength and Conditioning Research*, 25(2), 379-385.
- McMahon, J. J., Jones, P. A., & Comfort, P. (2015). A correction equation for jump height measured using the just jump system. *International Journal of Sports Physiology and Performance*, 11(4), 555-557.

- McMahon, J. J., Murphy, S., Rej, S. J. E., & Comfort, P. (2016). Countermovement jump phase characteristics of senior and academy rugby league players. *International Journal of Sports Physiology and Performance*, Published ahead of print.
- McMaster, D. T. W. (2015). *Methods of assessing, monitoring and improving strength and ballistic performance in highly trained rugby union players*. (Doctor of Philosophy), Auckland University of Technology.
- McMaster, D. T. W., Gill, N., Cronin, J., & McGuigan, M. (2013). The development, retention and decay rates of strength and power in elite rugby union, rugby league and american football. *Sports Med*, 43(5), 367-384.
- McNamara, D. J., Gabbett, T. J., Naughton, G., Farhart, P., & Chapman, P. (2013). Training and competition workloads and fatigue responses of elite junior cricket players. *International Journal of Sports Physiology and Performance*, 8(5), 517-526.
- Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D., . . . Urhausen, A. (2013). Prevention, Diagnosis, and Treatment of the Overtraining Syndrome: Joint Consensus Statement of the European College of Sport Science and the American College of Sports Medicine. *Med Sci Sports Exerc*, 45(1), 186-205.
- Meeusen, R., Duclos, M., Gleeson, M., Rietjens, G., Steinacker, J., & Urhausen, A. (2006). Prevention, diagnosis and treatment of the Overtraining Syndrome - ECSS Position Statement 'Task Force'. *European Journal of Sport Science*, 6(1), 1-14.
- Meeusen, R., Watson, P., Hasegawa, H., Roelands, B., & Piacentini, M. F. (2006). Central fatigue - The serotonin hypothesis and beyond. *Sports Med*, 36(10), 881-909.
- Mejri, M. A., Hammouda, O., Zouaoui, K., Chaouachi, A., Chamari, K., Ben Rayana, M. C., & Souissi, N. (2014). Effect of two types of partial sleep deprivation on Taekwondo players' performance during intermittent exercise. *Biological Rhythm Research*, 45(1), 17-26.
- Micklewright, D., Griffin, M., Gladwell, V., & Beneke, R. (2005). Mood state response to massage and subsequent exercise performance. *Sport Psychologist*, 19(3), 234-250.
- Minett, G., Duffield, R., & Bird, S. P. (2010). Effects of acute multinutrient supplementation on rugby union game performance and recovery. *International Journal of Sports Physiology and Performance*, 5(1), 27-41.
- Minett, G. M., & Duffield, R. (2014). Is recovery driven by central or peripheral factors? A role for the brain in recovery following intermittent-sprint exercise. *Frontiers in Physiology*, 5, 24.
- Mohr, M., Krstrup, P., & Bangsbo, J. (2003). Match performance of high-standard soccer players with special reference to development of fatigue. *J Sports Sci*, 21(7), 519-528.
- Moir, G., Button, C., Glaister, M., & Stone, M. H. (2004). Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in physically active men. *Journal of Strength and Conditioning Research*, 18(2), 276-280.
- Moir, G. L., Garcia, A., & Dwyer, G. B. (2009). Intersession reliability of kinematic and kinetic variables during vertical jumps in men and women. [- 2009]. *International Journal of Sports Physiology and Performance*, 4(3), 317-330.
- Montgomery, P. G., Pyne, D. B., Cox, A. J., Hopkins, W. G., Minahan, C. L., & Hunt, P. H. (2008). Muscle damage, inflammation, and recovery interventions during a 3-day basketball tournament. *European Journal of Sport Science*, 8(5), 241-250.
- Mooney, M. G., Cormack, S., O'Brien, B. J., Morgan, W. M., & McGuigan, M. (2013). Impact of neuromuscular fatigue on match exercise intensity and performance in elite Australian football. *Journal of Strength and Conditioning Research*, 27(1), 166-173.
- Moore, D. R., Robinson, M. J., Fry, J. L., Tang, J. E., Glover, E. I., Wilkinson, S. B., . . . Phillips, S. M. (2009). Ingested protein dose response of muscle and albumin protein synthesis after resistance exercise in young men. *American Journal of Clinical Nutrition*, 89(1), 161-168.
- Morales, J., Alamo, J. M., Garcia-Masso, X., Busca, B., Lopez, J. L., Serra-Ano, P., & Gonzalez, L. M. (2014). Use of heart rate variability in monitoring stress and recovery in judo athletes. *Journal of Strength and Conditioning Research*, 28(7), 1896-1905.
- Moraska, A. (2005). Sports massage - A comprehensive review. *Journal of Sports Medicine and Physical Fitness*, 45(3), 370-380.

- Morel, B., Rouffet, D. M., Bishop, D. J., Rota, S. J., & Hautier, C. A. (2015). Fatigue induced by repeated maximal efforts is specific to the rugby task performed. *International Journal of Sports Science & Coaching*, 10(1), 11-20.
- Mourot, L., Bouhaddi, M., Tordi, N., Rouillon, J. D., & Regnard, J. (2004). Short and long-term effects of a single bout of exercise on heart rate variability: comparison between constant and interval training exercises. *Eur J Appl Physiol*, 92(4-5), 508-517.
- Mujika, I., & Burke, L. M. (2010). Nutrition in team sports. *Annals of Nutrition and Metabolism*, 57(2), 26-35.
- Murphy, A. J., & Wilson, G. J. (1996). Poor correlations between isometric tests and dynamic performance: Relationship to muscle activation. *European Journal of Applied Physiology and Occupational Physiology*, 73(3-4), 353-357.
- Murphy, A. P., Snape, A. E., Minett, G. M., Skein, M., & Duffield, R. (2013). The effect of post-match alcohol ingestion on recovery from competitive rugby league matches. *Journal of Strength and Conditioning Research*, 27(5), 1304-1312.
- Murray, A., & Cardinale, M. (2015). Cold applications for recovery in adolescent athletes: a systematic review and meta analysis. *Extreme Physiology and Medicine*, 4(1), 17-17.
- Murray, N. B., Gabbett, T. J., & Chamari, K. (2014). Effect of different between-match recovery times on the activity profiles and injury rates of national rugby league players. *Journal of Strength and Conditioning Research*, 28(12), 3476-3483.
- Myer, G. D., Paterno, M. V., Ford, K. R., & Hewett, T. E. (2008). Neuromuscular training techniques to target deficits before return to sport after anterior cruciate ligament reconstruction. *Journal of Strength and Conditioning Research*, 22(3), 987-1014.
- Nagahara, R., Morin, J.-B., & Koido, M. (2016). Impairment of sprint mechanical properties in an actual soccer match: A pilot study. *International Journal of Sports Physiology and Performance*, 11(7), 893-898.
- Nedelec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., & Dupont, G. (2012). Recovery in soccer part I - Post-match fatigue and time course of recovery. *Sports Med*, 42(12), 997-1015.
- Nedelec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., & Dupont, G. (2013). Recovery in soccer part II-Recovery strategies. *Sports Med*, 43(1), 9-22.
- Nibali, M. L., Tombleson, T., Brady, P. H., & Wagner, P. (2015). Influence of familiarization and competitive level on the reliability of countermovement vertical jump kinetic and kinematic variables. *Journal of Strength and Conditioning Research*, 29(10), 2827-2835.
- Nicholas, C. W., Tsintzas, K., Boobis, L., & Williams, C. (1999). Carbohydrate-electrolyte ingestion during intermittent high-intensity running. *Med Sci Sports Exerc*, 31(9), 1280-1286.
- Nicholls, A. R., Backhouse, S. H., Polman, R. C. J., & McKenna, J. (2009). Stressors and affective states among professional rugby union players. *Scandinavian Journal of Medicine & Science in Sports*, 19(1), 121-128.
- Noakes, T., & Du Plessis, M. (1996). *Rugby without risk: A practical guide to the prevention & treatment of rugby injuries*. Pretoria: van Schaik Publishers.
- Noakes, T. D. (2000). Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance. *Scandinavian Journal of Medicine & Science in Sports*, 10(3), 123-145.
- Noakes, T. D. (2002). *The lore of running* (4th edition ed.). Champaign, IL: Human Kinetics.
- Noakes, T. D. (2012). The Central Governor Model in 2012: eight new papers deepen our understanding of the regulation of human exercise performance. *Br J Sports Med*, 46(1), 1-3.
- Noakes, T. D., & Gibson, A. S. (2004). Logical limitations to the "catastrophe" models of fatigue during exercise in humans. *Br J Sports Med*, 38(5), 648-649.
- Noakes, T. D., Gibson, A. S., & Lambert, E. V. (2005). From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. *Br J Sports Med*, 39(2), 120-124.

- Noakes, T. D., Peltonen, J. E., & Rusko, H. K. (2001). Evidence that a central governor regulates exercise performance during acute hypoxia and hyperoxia. *Journal of Experimental Biology*, 204(18), 3225-3234.
- Noonan, V., & Dean, E. (2000). Submaximal exercise testing: Clinical application and interpretation. *Physical Therapy*, 80(8), 782-807.
- O'Gorman, D., Hunter, A., McDonnacha, C., & Kirwan, J. P. (2000). Validity of field tests for evaluating endurance capacity in competitive and international-level sports participants. *Journal of Strength and Conditioning Research*, 14(1), 62-67.
- Oliver, S. J., Costa, R. J. S., Laing, S. J., Bilzon, J. L. J., & Walsh, N. P. (2009). One night of sleep deprivation decreases treadmill endurance performance. *Eur J Appl Physiol*, 107(2), 155-161.
- Ortenblad, N., Westerblad, H., & Nielsen, J. (2013). Muscle glycogen stores and fatigue. *Journal of Physiology*, 591(18), 4405-4413.
- Osgnach, C., Poser, S., Bernardini, R., Rinaldo, R., & Di Prampero, P. E. (2009). Energy cost and metabolic power in elite soccer: A new match analysis approach. [2010]. *Medicine and Science in Sports Exercise*, 42(1), 170-178.
- Owen, N. J., Watkins, J., Kilduff, L. P., Bevan, H. R., & Bennett, M. A. (2014). Development of a criterion method to determine peak mechanical power output in a countermovement jump. *The Journal of Strength and Conditioning Research*, 28(6), 1552-1558.
- Parrado, E., Garcia, M. A., Ramos, J., Cervantes, J. C., Rodas, G., & Capdevila, L. (2010). Comparison of Omegawave system and Polar s810i to detect R-R intervals at rest. *Int J Sports Med*, 31(5), 336-341.
- Peake, J. M., Roberts, L. A., Figueiredo, V. C., Egner, I., Krog, S., Aas, S. N., . . . Raastad, T. (2016). The effects of cold water immersion and active recovery on inflammation and cell stress responses in human skeletal muscle after resistance exercise. *The Journal of Physiology*, *Published ahead of print*.
- Petrofsky, J. S., & Lind, A. R. (1980). The influence of temperature on the amplitude and frequency components of the EMG during brief and sustained isometric contractions. *European Journal of Applied Physiology and Occupational Physiology*, 44(2), 189-200.
- Pienaar, C., & Coetzee, B. (2013). Changes in selected physical, motor performance and anthropometric components of university-level rugby players after one microcycle of a combined rugby conditioning and plyometric training program. *Journal of Strength and Conditioning Research*, 27(2), 398-415.
- Plews, D. J., Laursen, P. B., Kilding, A. E., & Buchheit, M. (2012). Heart rate variability in elite triathletes, is variation in variability the key to effective training? A case comparison. *Eur J Appl Physiol*, 112(11), 3729-3741.
- Plews, D. J., Laursen, P. B., Kilding, A. E., & Buchheit, M. (2013). Evaluating training adaptation with heart-rate measures: a methodological comparison. *International Journal of Sports Physiology and Performance*, 8(6), 688-691.
- Plews, D. J., Laursen, P. B., Le Meur, Y., Hausswirth, C., Kilding, A. E., & Buchheit, M. (2014). Monitoring training with heart-rate variability: How much compliance is needed for valid assessment? *International Journal of Sports Physiology and Performance*, 9(5), 783-790.
- Plews, D. J., Laursen, P. B., Stanley, J., Kilding, A. E., & Buchheit, M. (2013). Training adaptation and heart rate variability in elite endurance athletes: Opening the door to effective monitoring. *Sports Med*, 43(9), 773-781.
- Poppendieck, W., Wegmann, M., Ferrauti, A., Kellmann, M., Pfeiffer, M., & Meyer, T. (2016). Massage and performance recovery: A meta-analytical review. *Sports Med*, 46(2), 183-204.
- Pournot, H., Bieuzen, F., Duffield, R., Lepretre, P. M., Cozzolino, C., & Hausswirth, C. (2011). Short term effects of various water immersions on recovery from exhaustive intermittent exercise. *Eur J Appl Physiol*, 111(7), 1287-1295.
- Pournot, H., Bieuzen, F., Louis, J., Fillard, J.-R., Barbiche, E., & Hausswirth, C. (2011). Time-course of changes in inflammatory response after whole-body cryotherapy multi exposures following severe exercise. *Plos One*, 6(7).

- Proske, U., & Morgan, D. L. (2001). Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. *Journal of Physiology-London*, 537(2), 333-345.
- Pumprla, J., Howorka, K., Groves, D., Chester, M., & Nolan, J. (2002). Functional assessment of heart rate variability: physiological basis and practical applications. *International Journal of Cardiology*, 84(1), 1-14.
- Pyne, D. B., & Martin, D. T. (2011). Fatigue-Insights from individual and team sports. In F. E. Marino (Ed.), *Regulation of fatigue in exercise* (pp. 177-185). New York: Nova Science.
- Quarrie, K. L., Feehan, M., Waller, A. E., Cooke, K. R., Williams, S., & McGee, R. (1996). The New Zealand rugby injury and performance project: Alcohol use patterns within a cohort of rugby players. *Addiction*, 91(12), 1865-1868.
- Quarrie, K. L., Handcock, P., Toomey, M. J., & Waller, A. E. (1996). The New Zealand rugby injury and performance project .4. Anthropometric and physical performance comparisons between positional categories of senior a rugby players. *Br J Sports Med*, 30(1), 53-56.
- Quarrie, K. L., Handcock, P., Waller, A. E., Chalmers, D. J., Toomey, M. J., & Wilson, B. D. (1995). The New Zealand rugby injury and performance project .3. Anthropometric and physical performance characteristics of players. *Br J Sports Med*, 29(4), 263-270.
- Quarrie, K. L., & Hopkins, W. G. (2007). Changes in player characteristics and match activities in Bledisloe Cup rugby union from 1972 to 2004. *J Sports Sci*, 25(8), 895-903.
- Quarrie, K. L., Hopkins, W. G., Anthony, M. J., & Gill, N. D. (2013). Positional demands of international rugby union: Evaluation of player actions and movements. *Journal of Science and Medicine in Sport*, 16(4), 353-359.
- Quarrie, K. L., Raftery, M., Blackie, J., Cook, C. J., Fuller, C. W., Gabbett, T. J., . . . Tucker, R. (2016). Managing player load in professional rugby union: a review of current knowledge and practices. [2016/08/09]. *Br J Sports Med*, *Published ahead of print*.
- Quarrie, K. L., & Wilson, B. D. (2000). Force production in the rugby union scrum. *J Sports Sci*, 18(4), 237-246.
- Raastad, T., & Hallen, J. (2000). Recovery of skeletal muscle contractility after high- and moderate-intensity strength exercise. *Eur J Appl Physiol*, 82(3), 206-214.
- Rahnama, N., Lees, A., & Reilly, T. (2006). Electromyography of selected lower-limb muscles fatigued by exercise at the intensity of soccer match-play. *Journal of Electromyography and Kinesiology*, 16(3), 257-263.
- Rahnama, N., Reilly, T., Lees, A., & Graham-Smith, P. (2003). Muscle fatigue induced by exercise simulating the work rate of competitive soccer. *J Sports Sci*, 21(11), 933-942.
- Rampinini, E., Alberti, G., Fiorenza, M., Riggio, M., Sassi, R., Borges, T. O., & Coutts, A. J. (2015). Accuracy of GPS devices for measuring high-intensity running in field-based team sports. *Int J Sports Med*, 36(1), 49-53.
- Rampinini, E., Bishop, D., Marcora, S. M., Bravo, D. F., Sassi, R., & Impellizzeri, F. M. (2007). Validity of simple field tests as indicators of match-related physical performance in top-level professional soccer players. *Int J Sports Med*, 28(3), 228-235.
- Rattray, B., Argus, C. K., Martin, K., Northey, J., & Driller, M. W. (2015). Is it time to turn our attention toward central mechanisms for post-exertional recovery strategies and performance? [- 2015]. *Frontiers in Physiology*, 6(79), March.
- Reardon, C., Tobin, D. P., & Delahunt, E. (2015). Application of individualised speed thresholds to interpret position specific running demands in elite professional rugby union: A GPS study. *Plos One*, 10(7), e0133410.
- Reardon, C., Tobin, D. P., Tierney, P., & Delahunt, E. (2016). Collision count in rugby union: A comparison of micro-technology and video analysis methods. [- 2016]. *J Sports Sci*, *Published ahead of print*.
- Reardon, C., Tobin, D. P., Tierney, P., & Delahunt, E. (2017). The worst case scenario: locomotor and collision demands of the longest periods of gameplay in professional rugby union. [- 2017]. *Plos One*, 12(5), e0177072.
- Reid, L. C., Cowman, J. R., Green, B. S., & Coughlan, G. F. (2013). Return to play in elite rugby union: Application of global positioning system technology in return-to-running programs. *Journal of Sport Rehabilitation*, 22(2), 122-129.

- Rhea, M. R. (2004). Determining the magnitude of treatment effects in strength training research through the use of the effect size. *Journal of Strength and Conditioning Research*, 18(4), 918-920.
- Robergs, R. A., Ghiasvand, F., & Parker, D. (2004). Biochemistry of exercise-induced metabolic acidosis. *American Journal of Physiology-Regulatory Integrative and Comparative Physiology*, 287(3), R502-R516.
- Roberts, L. A., Raastad, T., Cameron-Smith, D., Coombes, J. S., & Peake, J. M. (2014). Cold water immersion reduces chronic resistance training-induced adaptation. *Med Sci Sports Exerc*, 46(5), 246-246.
- Roberts, S. P., Stokes, K. A., Trewartha, G., Hogben, P., Doyle, J., & Thompson, D. (2011). Effect of combined carbohydrate-protein ingestion on markers of recovery after simulated rugby union match-play. *J Sports Sci*, 29(12), 1253-1262.
- Roberts, S. P., Trewartha, G., Higgitt, R. J., El-Abd, J., & Stokes, K. A. (2008). The physical demands of elite English rugby union. *J Sports Sci*, 26(8), 825-833.
- Robertson, A., Watt, J. M., & Galloway, S. D. R. (2004). Effects of leg massage on recovery from high intensity cycling exercise. *Br J Sports Med*, 38(2), 173-176.
- Robson-Ansley, P. J., Gleeson, M., & Ansley, L. (2009). Fatigue management in the preparation of Olympic athletes. *J Sports Sci*, 27(13), 1409-1420.
- Rodri'Guez-Marroyo, J. A., Villa, G., Garc'ıA-Lopez, J., & Foster, C. (2012). Comparison of heart rate and session RPE methods of defining exercise load in cyclists. *Journal of Strength and Conditioning Research*, 26(8), 2249-2257.
- Roe, G., Darrall-Jones, J., Black, C., Shaw, W., Till, K., & Jones, B. (2016). Validity of 10 Hz GPS and timing gates for assessing maximum velocity in professional rugby union players. *International Journal of Sports Physiology and Performance*, Published ahead of print.
- Roe, G., Darrall-Jones, J., Till, K., Phibbs, P., Read, D., Weakley, J., & Jones, B. (2015). Between-day reliability and sensitivity of common fatigue measures in rugby players. *International Journal of Sports Physiology and Performance*, 11(5), 581-586.
- Roe, G., Darrall-Jones, J., Till, K., Phibbs, P., Read, D., Weakley, J., . . . Jones, B. (2017). The effect of physical contact on changes in fatigue markers following rugby union field-based training. *European Journal of Sport Science*, 1-9.
- Ronglan, L. T., Raastad, T., & Borgesen, A. (2006). Neuromuscular fatigue and recovery in elite female handball players. *Scandinavian Journal of Medicine & Science in Sports*, 16(4), 267-273.
- Rowell, A. E., Aughey, R. J., Hopkins, W. G., Stewart, A. M., & Cormack, S. J. (2016). Identification of sensitive measures of recovery following external load from football match play. *International Journal of Sports Physiology and Performance*, Published ahead of print.
- Rowell, G. J., Coutts, A. J., Reaburn, P., & Hill-Haas, S. (2009). Effects of cold-water immersion on physical performance between successive matches in high-performance junior male soccer players. *J Sports Sci*, 27(6), 565-573.
- Rushall, B. S., & Pyke, F. S. (1990). *Training for sports and fitness*. Melbourne, Australia.: Macmillan Educational.
- Rushton, J. L., Davies, I., Horan, M. A., Mahon, M., & Williams, R. (1997). Production of consistent crush lesions of murine skeletal muscle in vivo using an electromechanical device. *Journal of Anatomy*, 190, 417-422.
- Russell, M., Northeast, J., Atkinson, G., Shearer, D. A., Sparkes, W., Cook, C. J., & Kilduff, L. P. (2015). Between-match variability of peak power output and creatine kinase responses to soccer match-play. *Journal of Strength and Conditioning Research*, 29(8), 2079-2085.
- Saw, A. E., Main, L. C., & Gustin, P. B. (2015). Monitoring athletes through self-report: Factors influencing implementation. *Journal of Sports Science and Medicine*, 14(1), 137-146.
- Saw, A. E., Main, L. C., & Gustin, P. B. (2016). Monitoring the athlete training response: subjective self-reported measures trump commonly used objective measures: a systematic review. *Br J Sports Med*, 50(5).
- Schaal, K., Le Meur, Y., Bieuzen, F., Petit, O., Hellard, P., Toussaint, J. F., & Hausswirth, C. (2013). Effect of recovery mode on postexercise vagal reactivation in elite synchronized

- swimmers. *Applied Physiology Nutrition and Metabolism-Physiologie Appliquee Nutrition Et Metabolisme*, 38(2), 126-133.
- Schaal, K., Le Meur, Y., Louis, J., Filliard, J.-R., Hellard, P., Casazza, G., & Hausswirth, C. (2015). Whole-body cryostimulation limits overreaching in elite synchronized swimmers. *Med Sci Sports Exerc*, 47(7), 1416-1425.
- Schimpchen, J., Wagner, M., Ferrauti, A., Kellmann, M., Pfeiffer, M., & Meyer, T. (2016). Can cold water immersion enhance recovery in elite Olympic weightlifters? An individualised perspective. *Journal of Strength and Conditioning Research*, Publish Ahead of Print.
- Schmidtbleicher, D. (1992). Training for power events. In K. P. V. (Ed.), *Strength and Power in Sport* (pp. 381-385). Oxford, England.: Blackwell.
- Schmikli, S. L., Brink, M. S., de Vries, W. R., & Backx, F. J. G. (2011). Can we detect non-functional overreaching in young elite soccer players and middle-long distance runners using field performance tests? *Br J Sports Med*, 45(8), 631-636.
- Schoeman, R., Coetzee, D., & Schall, R. (2015). Positional tackle and collision rates in Super Rugby. *International Journal of Performance Analysis in Sport*, 15(3), 1022-1036.
- Schumann, M., Eklund, D., Taipale, R. S., Nyman, K., Kraemer, W. J., Hakkinen, A., . . . Hakkinen, K. (2013). Acute neuromuscular and endocrine responses and recovery to single-session combined endurance and strength loadings: "Order effect" in untrained young men. *Journal of Strength and Conditioning Research*, 27(2), 421-433.
- Scott, M. T. U., Scott, T. J., & Kelly, V. G. (2016). The validity and reliability of global positioning systems in team sport: A brief review. *Journal of Strength and Conditioning Research*, 30(5), 1470-1490.
- Shearer, D. A., Jones, R. M., Kilduff, L. P., & Cook, C. J. (2015). Effects of competition on the sleep patterns of elite rugby union players. [- 2015/08/09]. *European Journal of Sport Science*, 15(8), 681-686.
- Shearer, D. A., Kilduff, L. P., Finn, C., Jones, R. M., Bracken, R. M., Mellalieu, S. D., . . . Cook, C. J. (2015). Measuring recovery in elite rugby players: The brief assessment of mood, endocrine changes, and power. *Research Quarterly for Exercise and Sport*, 86(4), 379-386.
- Shearer, D. A., Sparkes, W., Northeast, J., Cunningham, D. J., Cook, C. J., & Kilduff, L. P. (2016). Measuring recovery: An adapted Brief Assessment of Mood (BAM+) compared to biochemical and power output alterations. *Journal of Science and Medicine in Sport*, Published ahead of print.
- Shephard, R. J. (2001). Chronic fatigue syndrome. *Sports Med*, 31(3), 167-194.
- Sheppard, J. M., Gabbett, T. J., & Stanganelli, L.-C. (2009). An analysis of playing positions in elite men's volleyball: Considerations for competition demands and physiologic characteristics. *Journal of Strength and Conditioning Research*, 23(6), 1858-1866.
- Shirreffs, S. M., & Sawka, M. N. (2011). Fluid and electrolyte needs for training, competition, and recovery. *J Sports Sci*, 29(1), S39-S46.
- Shirreffs, S. M., Taylor, A. J., Leiper, J. B., & Maughan, R. J. (1996). Post-exercise rehydration in man: Effects of volume consumed and drink sodium content. *Med Sci Sports Exerc*, 28(10), 1260-1271.
- Skein, M., Duffield, R., Edge, J., Short, M. J., & Mundel, T. (2011). Intermittent-sprint performance and muscle glycogen after 30 h of sleep deprivation. *Med Sci Sports Exerc*, 43(7), 1301-1311.
- Skein, M., Duffield, R., Minett, G. M., Snape, A., & Murphy, A. (2013). The effect of overnight sleep deprivation after competitive rugby league matches on postmatch physiological and perceptual recovery. *International Journal of Sports Physiology and Performance*, 8(5), 556-564.
- Skurvydas, A., Jascaninas, J., & Zachovajevs, P. (2000). Changes in height of jump, maximal voluntary contraction force and low-frequency fatigue after 100 intermittent or continuous jumps with maximal intensity. *Acta Physiologica Scandinavica*, 169(1), 55-62.

- Slattery, K. M., Wallace, L. K., Murphy, A. J., & Coutts, A. J. (2006). Physiological determinants of three-kilometer running performance in experienced triathletes. *Journal of Strength and Conditioning Research*, 20(1), 47-52.
- Smart, D., Hopkins, W. G., Quarrie, K. L., & Gill, N. (2014). The relationship between physical fitness and game behaviours in rugby union players. *European Journal of Sport Science*, 14(1), S8-S17.
- Smart, D. J., Gill, N. D., Beaven, C. M., Cook, C. J., & Blazeovich, A. J. (2008). The relationship between changes in interstitial creatine kinase and game-related impacts in rugby union. *Br J Sports Med*, 42(3), 198-201.
- Smart, D. J., Hopkins, W. G., & Gill, N. D. (2013). Differences and changes in the physical characteristics of professional and amateur rugby union players. *Journal of Strength and Conditioning Research*, 27(11), 3033-3044.
- Smirmaul, B. P. C., Bertucci, D. R., & Teixeira, I. P. (2013). Is the VO(2) max that we measure really maximal? *Frontiers in Physiology*, 4, 1-4.
- Smith, C., Kruger, M. J., Smith, R. M., & Myburgh, K. H. (2008). The inflammatory response to skeletal muscle injury illuminating complexities. *Sports Med*, 38(11), 947-969.
- Soares-Caldeira, L. F., Ritti-Dias, R. M., Okuno, N. M., Cyrino, E. S., Gurjão, A. L. D., & Ploutz-Snyder, L. L. (2009). Familiarization indexes in sessions of 1-RM tests in adult women. *The Journal of Strength and Conditioning Research*, 23(7), 2039-2045.
- Sparks, M., & Coetsee, B. (2013). The use of heart rates and graded maximal test values to determine rugby union game intensities. *Journal of Strength and Conditioning Research*, 27(2), 507-513.
- Spencer, M., Bishop, D., Dawson, B., & Goodman, C. (2005). Physiological and metabolic responses of repeated-sprint activities - Specific to field-based team sports. *Sports Med*, 35(12), 1025-1044.
- Spencer, M., Lawrence, S., Rechichi, C., Bishop, D., Dawson, B., & Goodman, C. (2004). Time-motion analysis of elite field hockey, with special reference to repeated-sprint activity. *J Sports Sci*, 22(9), 843-850.
- Speranza, M. J. A., Gabbett, T. J., Johnston, R. D., & Sheppard, J. M. (2015). Muscular strength and power correlates of tackling ability in semiprofessional rugby league players. *Journal of Strength and Conditioning Research*, 29(8), 2071-2078.
- Stanley, J., Peake, J. M., & Buchheit, M. (2013). Cardiac parasympathetic reactivation following exercise: Implications for training prescription. *Sports Med*, 43(12), 1259-1277.
- StatSports. (2012). *StatSports Viper Metrics*. Newry, Northern Ireland: StatSports.
- Stephenson, D. G., Lamb, G. D., & Stephenson, G. M. M. (1998). Events of the excitation-contraction-relaxation (E-C-R) cycle in fast- and slow-twitch mammalian muscle fibres relevant to muscle fatigue. *Acta Physiologica Scandinavica*, 162(3), 229-245.
- Street, G., McMillan, S., Board, W., Rasmussen, M., & Heneghan, J. M. (2001). Sources of error in determining countermovement jump height with the impulse method. [- 2001]. *Journal of Applied Biomechanics*, 17(1), 43-54.
- Strojnik, V., & Komi, P. V. (1998). Neuromuscular fatigue after maximal stretch-shortening cycle exercise. *J Appl Physiol* (1985), 84, 344-350.
- Suarez-Arrones, L., Arenas, C., López, G., Requena, B., Terrill, O., & Mendez-Villanueva, A. (2014). Positional differences in match running performance and physical collisions in men rugby sevens. *International Journal of Sports Physiology and Performance*, 9(2), 316-323.
- Suzuki, M., Umeda, T., Nakaji, S., Shimoyama, T., Mashiko, T., & Sugawara, K. (2004). Effect of incorporating low intensity exercise into the recovery period after a rugby match. *Br J Sports Med*, 38(4), 436-440.
- Swinbourne, R. R. (2015). *Sleep, recovery and performance in collision sport athletes*. (Doctor of Philosophy), Auckland University of Technology, Auckland.
- Sykes, D., Nicholas, C., Lamb, K., & Twist, C. (2013). An evaluation of the external validity and reliability of a rugby league match simulation protocol. *J Sports Sci*, 31(1), 48-57.
- Takarada, Y. (2003). Evaluation of muscle damage after a rugby match with special reference to tackle plays. *Br J Sports Med*, 37(5), 416-419.

- Takeda, M., Sato, T., Hasegawa, T., Shintaku, H., Kato, H., Yamaguchi, Y., & Radak, Z. (2014). The effects of cold water immersion after rugby training on muscle power and biochemical markers. *Journal of Sports Science and Medicine*, 13(3), 616-623.
- Task Force Of The European Society Of, C., The North, A., Society Of, P., & Electrophysiology. (1996). Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *European Heart Journal*, 17(3), 354-381.
- Taylor, K.-L. (2012). *Monitoring neuromuscular fatigue in high performance athletes*. (Doctor of Philosophy Sports Science), Edith Cowan University, Faculty of Computing Health and Science.
- Taylor, K.-L., Chapman, D. W., Cronin, J. B., Newton, M. J., & Gill, N. (2012). Fatigue monitoring in high performance sport: A survey of current trends. *Journal of Australian Strength and Conditioning*, 20(1), 12-23.
- Taylor, K.-L., Cronin, J., Gill, N. D., Chapman, D. W., & Sheppard, J. M. (2010). Sources of variability in iso-inertial jump assessments. *International Journal of Sports Physiology and Performance*, 5(4), 546-558.
- Tee, J. C., Bosch, A. N., & Lambert, M. I. (2007). Metabolic consequences of exercise-induced muscle damage. *Sports Med*, 37(10), 827-836.
- Tee, J. C., & Coopoo, Y. (2015). Movement and impact characteristics of South African professional rugby union players. *South African Journal of Sports Medicine*, 27(2), 33-39.
- Tee, J. C., Lambert, M. I., & Coopoo, Y. (2016). Impact of fatigue on positional movements during professional rugby union match play. *International Journal of Sports Physiology and Performance*, Published ahead of print.
- Thomas, K., Dent, J., Howatson, G., & Goodall, S. (2017). Etiology and recovery of neuromuscular fatigue following simulated soccer match-play. *Medicine and Science in Sports & Exercise*, Published ahead of print.
- Thorlund, J. B., Aagaard, P., & Madsen, K. (2009). Rapid muscle force capacity changes after soccer match play. *Int J Sports Med*, 30(4), 273-278.
- Thorlund, J. B., Michalsik, L. B., Madsen, K., & Aagaard, P. (2008). Acute fatigue-induced changes in muscle mechanical properties and neuromuscular activity in elite handball players following a handball match. *Scandinavian Journal of Medicine & Science in Sports*, 18(4), 462-472.
- Thornton, H. R., Delaney, J. A., Duthie, G., Scott, B. R., Chivers, W. J., Sanctuary, C. E., & Dascombe, B. J. (2015). Predicting self-reported illness for professional team-sport athletes. *International Journal of Sports Physiology and Performance*, 11(4), 543-550.
- Thorpe, R. T., Strudwick, A. J., Buchheit, M., Atkinson, G., Drust, B., & Gregson, W. (2015). Monitoring fatigue during the in-season competitive phase in elite soccer players. *International Journal of Sports Physiology and Performance*, 10(8), 958-964.
- Tian, Y., He, Z.-H., Zhao, J.-X., Tao, D.-L., Xu, K.-Y., Earnest, C. P., & McNaughton, L. R. (2013). Heart rate variability threshold values for early-warning nonfunctional overreaching in elite female wrestlers. *Journal of Strength and Conditioning Research*, 27(6), 1511-1519.
- Tierney, P., Tobin, D. P., Blake, C., & Delahunt, E. (2016). Attacking 22 entries in rugby union: running demands and differences between successful and unsuccessful entries. [-2016]. *Scandinavian Journal of Medicine & Science in Sports*, Published ahead of print.
- Till, K., Jones, B., Darrall-Jones, J., Emmonds, S., & Cooke, C. (2015). Longitudinal development of anthropometric and physical characteristics within academy rugby league players. *Journal of Strength and Conditioning Research*, 29(6), 1713-1722.
- Till, K., Tester, E., Jones, B., Emmonds, S., Fahey, J., & Cooke, C. (2014). Anthropometric and physical characteristics of english academy rugby league players. *Journal of Strength and Conditioning Research*, 28(2), 319-327.
- Tipton, K. D., Rasmussen, B. B., Miller, S. L., Wolf, S. E., Owens-Stovall, S. K., Petrini, B. E., & Wolfe, R. R. (2001). Timing of amino acid-carbohydrate ingestion alters anabolic response of muscle to resistance exercise. *American Journal of Physiology-Endocrinology and Metabolism*, 281(2), E197-E206.

- Tobin, D. P., & Delahunt, E. (2014). The acute effect of a plyometric stimulus on jump performance in professional rugby players. *Journal of Strength and Conditioning Research*, 28(2), 367-372.
- Toji, H., Suei, K., & Kaneko, M. (1997). Effects of combined training loads on relations among force, velocity, and power development. *Canadian Journal of Applied Physiology-Revue Canadienne De Physiologie Appliquee*, 22(4), 328-336.
- Turki, O., Chaouachi, A., Drinkwater, E. J., Chtara, M., Chamari, K., Amri, M., & Behm, D. G. (2011). Ten minutes of dynamic stretching is sufficient to potentiate vertical jump performance characteristics. *Journal of Strength and Conditioning Research*, 25(9), 2453-2463.
- Turner, T. S., Tobin, D. P., & Delahunt, E. (2015). Peak power in the hexagonal barbell jump squat and its relationship to jump performance and acceleration in elite rugby union players. *The Journal of Strength and Conditioning Research*, 29(5), 1234-1239.
- Twist, C., & Eston, R. G. (2009). The effect of exercise-induced muscle damage on perceived exertion and cycling endurance performance. *Eur J Appl Physiol*, 105(4), 559-567.
- Twist, C., & Highton, J. (2013). Monitoring fatigue and recovery in rugby league players. *International Journal of Sports Physiology and Performance*, 8(5), 467-474.
- Twist, C., Highton, J., Daniels, M., Mill, N., & Close, G. L. (2017). Intensified fixture schedule in professional rugby league: A case study. *International Journal of Sports Physiology & Performance*, Published ahead of print.
- Twist, C., Highton, J., Waldron, M., Edwards, E., Austin, D., & Gabbett, T. J. (2014). Movement demands of elite rugby league players during Australian national rugby league and european super league matches. *International Journal of Sports Physiology and Performance*, 9(6), 925-930.
- Twist, C., & Sykes, D. (2011). Evidence of exercise-induced muscle damage following a simulated rugby league match. *European Journal of Sport Science*, 11(6), 401-409.
- Twist, C., Waldron, M., Highton, J., Burt, D., & Daniels, M. (2012). Neuromuscular, biochemical and perceptual post-match fatigue in professional rugby league forwards and backs. *J Sports Sci*, 30(4), 359-367.
- Varley, M. C., Fairweather, I. H., & Aughey, R. J. (2012). Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *J Sports Sci*, 30(2), 121-127.
- Venter, R. E., Opperman, E., & Opperman, S. (2011). The use of Global Positioning System (GPS) tracking devices to assess movement demands and impacts in Under-19 rugby union match play : sports technology. *African Journal for Physical Health Education, Recreation and Dance*, 17(1), 8.
- Verdijk, L. B., van Loon, L., Meijer, K., & Savelberg, H. H. C. M. (2009). One-repetition maximum strength test represents a valid means to assess leg strength in vivo in humans. *J Sports Sci*, 27(1), 59-68.
- Vernillo, G., Agnello, L., Barbuti, A., Di Meco, S., Lombardi, G., Merati, G., & La Torre, A. (2015). Postexercise autonomic function after repeated-sprints training. *Eur J Appl Physiol*, 115(11), 2445-2455.
- Veugelaers, K. R., Young, W. B., Fahrner, B., & Harvey, J. T. (2015). Different methods of training load quantification and their relationship to injury and illness in elite Australian football. *Journal of Science and Medicine in Sport*, 19(1), 24-28.
- Vicente-Campos, D., Lopez, A. M., Nunez, M. J., & Chicharro, J. L. (2014). Heart rate recovery normality data recorded in response to a maximal exercise test in physically active men. *Eur J Appl Physiol*, 114(6), 1123-1128.
- Vukovich, M. D., Schoorman, R., Heilman, C., Jacob, P., & Benowitz, N. L. (2005). Caffeine-herbal ephedra combination increases resting energy expenditure, heart rate and blood pressure. *Clinical and Experimental Pharmacology and Physiology*, 32(1-2), 47-53.
- Waldron, M., Twist, C., Highton, J., Worsfold, P., & Daniels, M. (2011). Movement and physiological match demands of elite rugby league using portable global positioning systems. *J Sports Sci*, 29(11), 1223-1230.
- Wallace, L., Coutts, A., Bell, J., Simpson, N., & Slaterry, K. M. (2008). Using session-rpe to monitor training load in swimmers. *Strength and Conditioning Journal*, 30(6), 72-76.

- Wallace, L. K., Slattery, K. M., & Coutts, A. J. (2009). The Ecological Validity and Application of the Session-RPE Method for Quantifying Training Loads in Swimming. *Journal of Strength and Conditioning Research*, 23(1), 33-38.
- Walsh, M. S., Ford, K. R., Bangen, K. J., Myer, G. D., & Hewett, T. E. (2006). The validation of a portable force plate for measuring force-time data during jumping and landing tasks. *Journal of Strength and Conditioning Research*, 20(4), 730-734.
- Warrington, G., Ryan, C., Murray, F., Duffy, P., & Kirwan, J. P. (2001). Physiological and metabolic characteristics of elite tug of war athletes. *Br J Sports Med*, 35(6), 396-401.
- Webb, N. P., Harris, N. K., Cronin, J. B., & Walker, C. (2013). The relative efficacy of three recovery modalities after professional rugby league matches. *Journal of Strength and Conditioning Research*, 27(9), 2449-2455.
- Wellman, A. D., Coad, S. C., Goulet, G. C., Coffey, V. G., & McLellan, C. P. (2016). Quantification of accelerometer derived impacts associated with competitive games in ncaa division I college football players. *Journal of Strength and Conditioning Research*, Published ahead of print.
- West, D. J., Cunningham, D. J., Bracken, R. M., Bevan, H. R., Crewther, B. T., Cook, C. J., & Kilduff, L. P. (2013). Effects of resisted sprint training on acceleration in professional rugby union players. *Journal of Strength and Conditioning Research*, 27(4), 1014-1018.
- West, D. J., Finn, C. V., Cunningham, D. J., Shearer, D. A., Jones, M. R., Harrington, B. J., . . . Kilduff, L. P. (2014). Neuromuscular function, hormonal, and mood responses to a professional rugby union match. *Journal of Strength and Conditioning Research*, 28(1), 194-200.
- White, G. E., & Wells, G. D. (2013). Cold-water immersion and other forms of cryotherapy: physiological changes potentially affecting recovery from high-intensity exercise. *Extreme Physiology and Medicine*, 2(1), 26-26.
- Wilmore, J. H., & Costill, D. L. (1999). *Physiology of sport and exercise* (2nd ed.). Champaign, IL: Human Kinetics.
- Windt, J., & Gabbett, T. (2016). How do training and competition workloads relate to injury? The workload—injury aetiology model. *Br J Sports Med*, Published ahead of print.
- Winter, E. M., Abt, G., Brookes, F. B. C., Challis, J. H., Fowler, N. E., Knudson, D. V., . . . Yeadon, M. R. (2016). Misuse of “power” and other mechanical terms in sport and exercise science research. *Journal of Strength and Conditioning Research*, 30(1), 292-300.
- Wood, D. J., Coughlan, G., & Delahunt, E. (2016). Fitness profiles of elite adolescent Irish rugby union players. *The Journal of Strength and Conditioning Research*, Published ahead of print.
- Yamane, M., Ohnishi, N., & Matsumoto, T. (2015). Does regular post-exercise cold application attenuate trained muscle adaptation? *Int J Sports Med*, 36(8), 647-653.
- Yamane, M., Teruya, H., Nakano, M., Ogai, R., Ohnishi, N., & Kosaka, M. (2006). Post-exercise leg and forearm flexor muscle cooling in humans attenuates endurance and resistance training effects on muscle performance and on circulatory adaptation. *Eur J Appl Physiol*, 96(5), 572-580.
- Young, W., MacDonald, C., Heggen, T., & Fitzpatrick, J. (1997). An evaluation of the specificity, validity and reliability of jumping tests. *Journal of Sports Medicine and Physical Fitness*, 37(4), 240-245.
- Young, W. B., MacDonald, C., & Flowers, M. A. (2001). Validity of double- and single-leg vertical jumps as tests of leg extensor muscle function. *Journal of Strength and Conditioning Research*, 15(1), 6-11.
- Zemski, A. J., Slater, G. J., & Broad, E. M. (2015). Body composition characteristics of elite Australian rugby union athletes according to playing position and ethnicity. *J Sports Sci*, 33(9), 970-978.

readiness. (n.d.) In *Cambridge Dictionary Online*. Retrieved May 20, 2015 from <http://dictionary.cambridge.org/dictionary/british/readiness?q=readiness>

fatigue state. (n.d.) In *Medical Dictionary*. Retrieved September 18 2015 from <http://medical-dictionary.thefreedictionary.com/fatigue+state>

Grainger, A. T., Ripley, N., & Comfort, P. (In Review). Comparison between a 6 second and 30 second cycle ergometer test for peak power in elite rugby union players.

11 Appendix

11.1 Appendix A

WEEKLY WELL-BEING MONITOR							
SCHEDULE:	MON	TUE	WED	THU	FRI	SAT	SUN
SLEEP QUALITY (record figure from 1-10 that best relates to your sleep quality from last night)							
10 = undisturbed							
9							
8							
7							
6							
5							
4							
3							
2							
1 = little/none							
ENERGY LEVELS (record figure from 1-10 that best relates to your energy levels this morning)							
10 = fresh							
9							
8							
7							
6							
5							
4							
3							
2							
1 = exhausted							
MUSCLE SORENESS (record figure from 1-10 that best relates to your body condition)							
10 = no pain							
9							
8							
7							
6							
5							
4							
3							
2							
1 = pain interrupting training							
MOOD (record figure from 1-10 that best relates to your mood)							
10 = motivated							
9							
8							
7							
6							
5							
4							
3							
2							
1 = negative							
APPETITE (record figure from 1-10 that best relates to your appetite)							
10 = excellent							
9							
8							
7							
6							
5							
4							
3							
2							
1 = none							
SUMMARY							
DAILY SCORES (TOTAL):							
WEEKLY AVERAGE SCORE:							

Figure 11.1: Example well-being questionnaire relating to Chapter

11.2 Appendix B

Table 11.1: Descriptive (mean \pm standard deviations) and reliability statistics, within testing days for Impulse (N.s) and concentric power (W) relating to Chapter 5

CMJ	Day 1 average	Day 1 %CV	Day 2 average	Day 2 %CV	Day 3 average	Day 3 %CV	All sessions average	Average %CV
CMJ Impulse (N.s)	229 \pm 4.1	1.7%	224 \pm 8.1	3.6%	222 \pm 7.3	3.2%	225 \pm 6.5	2.8%
CMJ Peak Concentric Power (W)	4661 \pm 109	2.2%	4493 \pm 466	10.5%	4367 \pm 88	2.0%	4507 \pm 121	2.6%

Table 11.2: Descriptive (mean \pm standard deviations) and reliability statistics, between testing days for Impulse (N.s) and concentric power (W) relating to Chapter 5

Jump	Day 1 (cm)	Day 2 (cm)	Day 3 (cm)	ICC r	Partial eta squared	SEM (cm)	SDD (cm)
CMJ Impulse Force Plate (N.s)	228 \pm 18.6	223 \pm 22.7	221 \pm 22.5	0.847	0.090	8.5	23.7 (10.60%)
CMJ Peak Concentric Power Force Plate (W)	4661 \pm 450	4493 \pm 547	4367 \pm 453	0.851	0.224	188.2	521.7 (11.5%)

11.3 Appendix C

Table 11.3: Descriptive (mean± StDv; CI=95% confidence intervals) across selected match demands data for all positions relating to Chapter 3

Position	Prop	Hooker	Lock	Back Row	Scrum Half	Out Half	Centre	Wing	Full Back
Game Time (mins)	61.2 ± 14.2 (CI 57.7-64.8)	56.6 ± 16.8 (CI 50.6-60.5)	70.6 ± 10.8 $\chi \hat{u}$ (CI 67.7-73.4)	70.9 ± 14.3 ∞ (CI 68.0-73.8)	63.7 ± 11.8 (CI 59.5-67.8)	66.3 ± 14.2 (CI 64.1-71.3)	76.0 ± 9.4 \pounds (CI 73.5-78.4)	73.2 ± 13.9 \S (CI 69.7-76.7)	77.0 ± 8.0 *# (CI 73.8-80.1)
Intensity (m/min)	59.6 ± 5.4 (CI 58.2-60.9)	66.7 ± 4.9 μ (CI 64.9-68.4)	66.5 ± 6.7 Ψ (CI 64.7-68.2)	64.8 ± 5.6 Ψ (CI 63.6-65.9)	74.4 ± 6.5 $\zeta \theta$ (CI 72.1-76.6)	71.9 ± 5.1 $\phi \varphi \varpi$ (CI 70.1-73.7)	68.1 ± 8.1 Ψ (CI 65.9-70.2)	69.0 ± 6.4 $\Psi \xi$ (CI 67.4-70.7)	76.2 ± 6.1 $\Omega \alpha$ (CI 73.8-78.6)
Accelerations	13.6 ± 7.0 (CI 11.9-15.3)	21.5 ± 9.9 (CI 18.0-25.0)	26.6 ± 9.3 Ψ (CI 24.1-29.0)	24.7 ± 13.6 Ψ (CI 21.9-27.4)	31.5 ± 10.7 $\Psi +$ (CI 27.7-35.2)	37.5 ± 10.3 $\pounds \eta$ (CI 33.9-41.1)	29.2 ± 8.9 Ψ (CI 26.9-31.5)	34.1 ± 11.3 $\pounds \nu A$ (CI 31.2-37.0)	32.6 ± 7.5 $\Psi \chi$ (CI 29.6-35.5)
Decelerations	20.3 ± 7.7 (CI 18.4-22.2)	28.9 ± 11.8 (CI 24.7-33.1)	34.5 ± 10.8 Ψ (CI 31.6-37.3)	36.0 ± 16.7 Ψ (CI 32.6-39.4)	35.1 ± 9.4 Ψ (CI 31.8-38.4)	43.4 ± 12.9 $\Psi \beta$ (CI 38.8-47.9)	43.6 ± 10.8 $\Psi \Delta$ \dagger (CI 40.8-46.5)	42.8 ± 13.4 $\pounds \star \hat{w}$ (CI 39.4-46.2)	46.0 ± 9.8 \pounds (CI 42.1-48.9)
Ψ significantly greater (p<0.001) compared to Props Ω significantly greater (p=0.03) compared to Out Halves and Wings η significantly greater (p=0.006) compared to Locks ν significantly greater (p=0.002) compared to Locks $*$ significantly greater (p=0.01) compared to Scrum Half and Hookers $\#$ significantly greater (p=0.003) compared to Props \pounds significantly greater (p<0.001) compared to Props and Hookers \S significantly greater (p=0.001) compared to Props and Hookers ∞ significantly greater (p=0.01) compared to Props and Hookers χ significantly greater (p=0.03) compared to Hookers φ significantly greater (p=0.004) compared to Hookers μ significantly greater (p=0.001) compared to Props $+$ significantly greater (p=0.01) compared to Hookers \star significantly greater (p=0.03) compared to Scrum Halves					ϕ significantly greater (p<0.001) compared to Props and Back Row ξ significantly greater (p=0.003) compared to Back Row α significantly greater (p<0.001) compared to Props, Hookers, Locks and Back Row χ significantly greater (p=0.03) compared to Hookers β significantly greater (p=0.007) compared to Hookers Δ significantly greater (p=0.008) compared to Locks θ significantly greater (p=0.005) compared to Locks \hat{u} significantly greater (p=0.03) compared to Props ζ significantly greater (p<0.001) compared to Props, Hookers and Back Row ϖ significantly greater (p=0.03) compared to Locks A significantly greater (p=0.01) compared to Back Row \dagger significantly greater (p=0.002) compared to Hookers \hat{w} significantly greater (p=0.01) compared to Locks				

Table 11.4: Descriptive (mean± StDv; CI=95% confidence intervals) across distance data for all positions relating to Chapter 3 (symbols presented on Table 11.5)

Position	Prop	Hooker	Lock	Back Row	Scrum Half	Out Half	Centre	Wing	Full Back
Distance (m)	4285 ± 893 (CI 4065-4505)	4469 ± 1238 (CI 4029-4908)	5517 ± 979 Ψ (CI 5259-5774)	5411 ± 1134 ⌘ Ψ (CI 5181-5641)	5408 ± 978 ≠ (CI 5067-5750)	5583 ± 1191 ≠ (CI 5167-5999)	6043 ± 966 ¶ Ψ (CI 5791-6295)	5926 ± 1295 ¥ (CI 5597-6255)	6904 ± 740 \$ £ € (CI 6617-7191)
Distance Zone 1 (m)	1799 ± 487 (CI 1679-1919)	1474 ± 429 (CI 1322-1627)	1963 ± 479 (CI 1837-2089)	2043 ± 482 i (CI 1945-2141)	1692 ± 381 (CI 1559-1825)	2029 ± 499 (CI 1855-2203)	2405 ± 456 B K ▲ (CI 2286-2524)	2337 ± 562 Ψ Γ Σ A £ (CI 2194-2480)	2328 ± 371 ¢ € ≈ (CI 2184-2472)
Distance Zone 2 (m)	1043 ± 319 (CI 965-1122)	1451 ± 410 # (CI 1306-1597)	1748 ± 383 Ψ ☼ (CI 1647-1849)	1663 ± 382 Ψ ★ (CI 1586-1741)	1421 ± 273 ≠ (CI 1325-1716)	1439 ± 269 ≠ (CI 1345-1533)	1574 ± 338 Ψ (CI 1485-1662)	1446 ± 400 Ψ (CI 1344-1548)	2078 ± 275 ¤ π ϖ Ⓜ u (CI 1971-2185)
Distance Zone 3 (m)	847 ± 210 (CI 795-899)	926 ± 296 (CI 821-1031)	1046 ± 306 ≠ x (CI 965-1127)	863 ± 244 (CI 814-913)	971 ± 217 (CI 895-1047)	948 ± 228 (CI 869-1028)	824 ± 225 (CI 766-883)	861 ± 263 (CI 794-928)	1042 ± 199 (CI 965-1119)
Distance Zone 4 (m)	394 ± 124 (CI 364-425)	536 ± 223 (CI 457-615)	589 ± 240 Ψ (CI 526-580)	568 ± 254 Ψ (CI 517-620)	1009 ± 214 \$ ▲ ☒ ® (CI 934-1084)	848 ± 227 ^ Ψ Γ (CI 769-927)	748 ± 191 Ψ + ϖ þ (CI 698-798)	708 ± 230 Ψ (CI 650-767)	922 ± 177 ¥ ^ (CI 853-991)
Distance Zone 5 (m)	118 ± 56 ⌘ (CI 104-131)	73 ± 47 (CI 57-90)	142 ± 54 € (CI 127-156)	202 ± 119 ✓ € (CI 178-226)	281 ± 76 ¥ ^ ħ (CI 254-308)	273 ± 88 ¥ ^ (CI 242-304)	322 ± 107 \$ (CI 294-350)	346 ± 113 \$ (CI 317-374)	429 ± 118 \$ ♭ ♯ (CI 384-475)
Distance Zone 6 (m)	17 ± 23 β (CI 11-23)	4 ± 10 (CI 1-8)	6 ± 9 (CI 3-8)	20 ± 24 + ŵ (CI 15-25)	33 ± 21 ^ € (CI 25-40)	43 ± 35 û ^ € (CI 31-55)	51 ± 42 \$ (CI 40-62)	139 ± 72 \$ © (CI 120-157)	101 ± 50 \$ ° v (CI 82-121)

Table 11.5: Key for descriptive distance data in Table 11.6 relating to Chapter 3

<p>* significantly greater (p=0.01) compared to Scrum Half and Hookers</p> <p># significantly greater (p=0.003) compared to Props</p> <p>¥ significantly greater (p<0.001) compared to Props and Hookers</p> <p>§ significantly greater (p=0.001) compared to Props and Hookers</p> <p>∞ significantly greater (p=0.01) compared to Props and Hookers</p> <p>⌘ significantly greater (p=0.03) compared to Hookers</p> <p>\$ significantly greater (p<0.001) compared to Props, Hookers, Locks and Back Row</p> <p>£ significantly greater (p=0.001) compared to Scrum Half</p> <p>€ significantly greater (p=0.003) compared to Out Half</p> <p>¶ significantly greater (p=0.002) compared to Hookers</p> <p>≠ significantly greater (p=0.002) compared to Props</p> <p>Ψ significantly greater (p<0.001) compared to Props</p> <p>Ω significantly greater (p=0.03) compared to Out Halves and Wings</p> <p>α significantly greater (p<0.001) compared to Props, Hookers, Locks, Back Row and Wings</p> <p>χ significantly greater (p=0.03) compared to Hookers</p> <p>Γ significantly greater (p=0.001) compared to Hookers</p> <p>Σ significantly greater (p=0.004) compared to Locks</p> <p>¢ significantly greater (p=0.005) compared to Props and Locks</p> <p>⌘ significantly greater (p<0.001) compared to Hookers</p> <p>≈ significantly greater (p=0.004) compared to Scrum Halves</p> <p>▣ significantly greater (p<0.001) compared to Props, Scrum Half and Out Half</p> <p>u significantly greater (p=0.001) compared to Centre</p> <p>♣ significantly greater (p=0.001) compared to Wingers</p> <p>★ significantly greater (p=0.03) compared to Scrum Halves</p> <p>⊠ significantly greater (p=0.002) compared to Centre</p> <p>^ significantly greater (p<0.001) compared to Locks</p> <p>♭ significantly greater (p=0.002) compared to Scrum Halves</p> <p>♫ significantly greater (p=0.001) compared to Out Halves</p> <p>Ⓟ significantly greater (p<0.001) compared to Scrum Half, Out Half and Centre</p> <p>√ significantly greater (p=0.01) compared to Out Halves</p>	<p>ζ significantly greater (p<0.001) compared to Props, Hookers and Back Row</p> <p>ϕ significantly greater (p<0.001) compared to Props and Back Row</p> <p>⌘ significantly greater (p=0.03) compared to Locks</p> <p>β significantly greater (p=0.007) compared to Hookers</p> <p>ξ significantly greater (p=0.003) compared to Back Row</p> <p>π significantly greater (p=0.003) compared to Hooker and Wings</p> <p>A significantly greater (p=0.01) compared to Back Row</p> <p>B significantly greater (p<0.001) compared to Props, Hookers, Locks and Scrum Half</p> <p>K significantly greater (p=0.001) compared to Back Row</p> <p>i significantly greater (p=0.002) compared to Hookers</p> <p>x significantly greater (p=0.004) compared to Centre</p> <p>♣ significantly greater (p=0.005) compared to Back Row</p> <p>® significantly greater (p=0.01) compared to Wingers</p> <p>♣ significantly greater (p=0.03) compared to Out Halves</p> <p>+ significantly greater (p=0.01) compared to Hookers</p> <p>♭ significantly greater (p=0.004) compared to Back Row</p> <p>♣ significantly greater (p=0.03) compared to Back Row</p> <p>✓ significantly greater (p=0.005) compared to Props</p> <p>◦ significantly greater (p=0.003) compared to Scrum Halves</p> <p>û significantly greater (p=0.03) compared to Props</p> <p>ŵ significantly greater (p=0.001) compared to Locks</p>
--	--

Table 11.6: Descriptive (mean± StDv; CI=95% confidence intervals) across impacts data for all positions relating to Chapter 3

Position	Prop	Hooker	Lock	Back Row	Scrum Half	Out Half	Centre	Wing	Full Back
Impacts > Zone 3	259 ± 250 (CI 198-321)	291 ± 145 ε ■ (CI 239-342)	157 ± 40 (CI 146-167)	225 ± 109 (CI 203-247)	274 ± 145 τ (CI 223-324)	186 ± 77 (CI 159-213)	229 ± 186 (CI 180-278)	197 ± 155 (CI 158-237)	296 ± 99 Θ Π Ω★ (CI 257-334)
Impacts Zone 1	1178 ± 313 (CI 1100-1255)	1820 ± 549 ^ (CI 1625-2015)	2232 ± 533 ¢ (CI 2092-2373)	2019 ± 476 ¢ (CI 1922-2115)	1998 ± 566 ¢ (CI 1800-2195)	2042 ± 528 ¢ (CI 1857-2226)	2053 ± 441 ¢ (CI 1938-2168)	1901 ± 521 ¢ (CI 1768-2033)	2553 ± 510 ¢ □ K Ω + (CI 2355-2751)
Impacts Zone 2	716 ± 195 (CI 668-764)	900 ± 326 (CI 785-1016)	845 ± 201β (CI 792-898)	815 ± 259 (CI 762-868)	1107 ± 234 ¢ ε ■ ¶ i x (CI 1025-1188)	948 ± 255 ∞ (CI 859-1038)	762 ± 337 (CI 674-850)	748 ± 252 (CI 684-812)	902 ± 182 α (CI 832-973)
Impacts Zone 3	323 ± 128 ε (CI 292-355)	379 ± 158 η (CI 323-435)	231 ± 76 (CI 211-251)	294 ± 135 (CI 267-322)	449 ± 166 ε γ ζ δ (CI 391-507)	307 ± 102 ι (CI 271-343)	274 ± 177 (CI 228-320)	273 ± 132 (CI 239-307)	341 ± 92 θ (CI 306-377)
Impacts Zone 4	130 ± 114 (CI 102-158)	148 ± 79 ε Ψ (CI 120-176)	75 ± 25 (CI 69-82)	112 ± 59 (CI 99-124)	162 ± 82 ε Π Ω (CI 133-191)	106 ± 41 π (CI 91-120)	111 ± 101 (CI 85-138)	100 ± 73 (CI 82-119)	142 ± 51 η (CI 122-162)
Impacts Zone 5	57 ± 67 (CI 40-73)	62 ± 35 ε Π ζ σ (CI 49-75)	30 ± 9 (CI 28-33)	46 ± 26 (CI 41-51)	58 ± 37 η (CI 45-72)	37 ± 20 (CI 29-44)	48 ± 48 (CI 35-61)	41 ± 37 (CI 31-50)	66 ± 27 η ρ Ω ★ (CI 55-76)
Impacts Zone 6	70 ± 74 (CI 51-88)	80 ± 33 φ ν χ i (CI 68-92)	49 ± 15 (CI 45-53)	67 ± 27 ω ® (CI 61-72)	52 ± 27 (CI 43-62)	42 ± 19 (CI 36-49)	66 ± 43 Ω (CI 54-77)	53 ± 49 (CI 40-65)	87 ± 27 ς Π ▲ § + (CI 76-97)
<p>Θ significantly greater (p=0.001) compared to Locks σ significantly greater (p=0.001) compared to Wingers Π significantly greater (p=0.03) compared to Back Row Ω significantly greater (p=0.03) compared to Out Half ε significantly greater (p<0.001) compared to Locks ν significantly greater (p=0.03) compared to Wingers τ significantly greater (p=0.002) compared to Locks ¢ significantly greater (p<0.001) compared to Props □ significantly greater (p=0.009) compared to Hookers K significantly greater (p=0.03) compared to Scrum Half + significantly greater (p=0.01) compared to Wingers ^ significantly greater (p=0.001) compared to Props Ψ significantly greater (p=0.02) compared to Wingers ■ significantly greater (p=0.009) compared to Back Row π significantly greater (p=0.004) compared to Locks ▲ significantly greater (p=0.005) compared to Scrum Half φ significantly greater (p=0.007) compared to Locks</p> <p>x significantly greater (p=0.03) compared to Full Backs ∞ significantly greater (p=0.01) compared to Props α significantly greater (p=0.03) compared to Props β significantly greater (p=0.01) compared to Props γ significantly greater (p=0.004) compared to Back Row δ significantly greater (p=0.008) compared to Wingers ζ significantly greater (p=0.009) compared to Out Half η significantly greater (p=0.001) compared to Locks θ significantly greater (p=0.003) compared to Locks ι significantly greater (p=0.005) compared to Locks ω significantly greater (p=0.03) compared to Locks</p> <p>ρ significantly greater (p=0.003) compared to Back Row ς significantly greater (p=0.006) compared to Lock § significantly greater (p=0.001) compared to Out Half χ significantly greater (p=0.003) compared to Out Half ® significantly greater (p=0.007) compared to Out Half ¶ significantly greater (p=0.03) compared to Centre i significantly greater (p=0.002) compared to Wingers ■ significantly greater (p=0.009) compared to Wingers ★significantly greater (p=0.03) compared to Wingers</p>									