A MIXED METHODS APPROACH TO TRAINING FOR THE MITIGATION OF MODIFIABLE RISK FACTORS FOR HAMSTRING STRAIN INJURY AND THE DEVELOPMENT OF ATHLETIC PERFORMANCE

Steven Ross

Ph.D. Thesis

2024

A MIXED METHODS APPROACH TO TRAINING FOR THE MITIGATION OF MODIFIABLE RISK FACTORS FOR HAMSTRING STRAIN INJURY AND THE DEVELOPMENT OF ATHLETIC PERFORMANCE

Steven Ross

University of Salford

School of Health and Society

Submitted in Partial Fulfilment of the Requirements for the Degree

of Doctor of Philosophy

October 2024

Table of Contents

List of Tables

`

List of Figures

List of Abbreviations

HSI – Hamstring strain injury

NHE – Nordic hamstring exercise

CMJ – Countermovement jump

CMJ-R – Countermovement rebound jump

RSImod – Modified reactive strength index

IMTP – Isometric midthigh pull

BFLH – Bicep femoris long head

BFSH – Biceo femoris short head

ST – Semitendinosus

SM – Semimembranosus

GMax – Gluteus maximus

MH – Medial hamstrings

2D – Two dimensional

3D – Three dimensional

GS – Gluteal squeeze

HS – Hamstring squeeze

MVIC – Maximal isometric voluntary contraction

MAN KNEE – Manually applied resistance to knee flexion

MAN HIP – Manually applied resistance to hip flexion

IKD KNEE – Isokinetic knee flexion

IKD HIP – Isokinetic hip extension

HSR – High-speed running

RDL – Romanian deadlift

GM – Good morning

MDT – Multidisciplinary team

EMG – Electromyography

sEMG – Surface electromyography

PF – Peak force

MF – Mean force

IF – Instantaneous force

FL – Fascicle length

S&C – Strength and conditioning

RR – Relative Risk

CI – Confidence interval

ICC – intra-class correlation coefficient

NCAA – National College Athletic Association

NSCA – National Strength and Conditioning Association

UKSCA – United Kingdom Strength and Conditioning Association

AE – Athlete exposures

MTU – Muscle tendon unit

MTJ – Muscle tendon junction

MT – Muscle thickness

LMM – Linear mixed model

CV – Coefficient of variation

IKD – Isokinetic dynamometer

PLR – Positive likelihood ratio

FHQ – Functional hamstring-to-quadricep

HQ – Hamstring-to-quadricep

PA – Pennation angle

SMD – Standardised mean difference

MDD – Minimum detectable difference

SEM – Standard error of measurement

ACL – Anterior cruciate ligament

RM – Repetition maximum

GPS – Global positioning system

DOMS – Delayed onset of muscle soreness

RMS – Root mean square

SD – Standard deviation

SPM – Statistical parametric mapping

vGRF – Vertical ground reaction force

SE – Standard error

Acknowledgements

Firstly, I would like to thank Professor Paul Comfort, Dr John McMahon and Dr Nick Ripley for the opportunity you have given me to study for a PhD and for the guidance and support you have provided me. My first experience of Paul and John was receiving what felt like an endless list of comments and criticisms on my original proposal, to which my good friend Dr Jamie Salter responded, “they’re going to tear you a new one in your interview”. Fortunately, Jamie’s predictions were not substantiated and our working relationship continued through multiple meetings and gallons of coffee. I am grateful for the addition of Dr Nick Ripley to my supervisory team, his uncanny ability to seemingly be able to recall every paper that has ever been written has been of great use as has his support and friendship. The approach to supervision from all three of you has helped me to strive for higher standards at every turn and for that I will always be grateful.

I would also like to thank those that have inspired and supported me throughout this journey. Dr Jamie Salter, Dr Adam Gledhill, Dr Matt Weston, Dr Rick Page, Dr Matt Cuthbert, Charlie Owen, Tim Horn and Professor Jason Lake. I’d also like to extend special thanks to Jack Fahey, Elliot Nash and Tass Watters, without your input, the final study in this thesis may never have happened!

Of course, without all those that volunteered to participate in my studies, there would be no thesis. Thank you to all of those that volunteered to take part, those that helped me with participant recruitment and to those that have provided critical input throughout.

Finally, I’d like to thank my family. My parents for providing me with the support and encouragement to go to university in the first place. Usually when people go to university for three years, maybe they will stick around a bit longer and do a Master’s.

I'm not quite sure you realised that once I started Uni, I'd seemingly never stop! After 14 continuous years of being a student, I promise that this will be the last graduation picture you'll have a find space for on the wall! Although with a career in academia now as well, it seems I'm still not leaving Uni! I'd like to thank my siblings - David, Peter and Dani - for putting up with me as the youngest of four, but I'm afraid now you'll have to put up with reading nearly 400 pages of my thesis (there will be a quiz at the end).

Most importantly, I'd like to thank my wife Jen, our little boy Freddie and our dog Milo. You have all been an endless source of motivation to be the best version of me that I can be. Jen, you have supported throughout my PhD journey. 7 years ago, you drove down to Southampton to celebrate with me when I got my offer to start my PhD, and we partied the night away in the Frog and Frigate. Since then (and back in the comfort of the north!) we've got a dog, bought a house, lived through a global pandemic, delivered our baby boy on our bathroom floor and got married. Through all of that, you have still supported me and pushed me to pursue my research. Freddie, without even knowing it, you have helped me on this journey that you didn't even know I was on. Your infectious laugh and amazingly creative imagination have been so valuable to me in those times when I've been sat staring at a screen and sifting through data for hours. Being able to step away from the screen to laugh with you and go head-to-head in countless Pokémon battles has helped me to reset, clear my head and, at times, remind myself why I was working towards my goals. I have no idea what you will do with your life, but I hope I can return the favour one day. Milo can't read, so I'll just get him some treats instead of trying to write anything sentimental for him. Having said that, I did do most of my thinking around this project while out on long walks with him, so he deserves some credit! I love you all. Thank you.

Abstract

Hamstring strain injuries (HSIs) are the most common non-contact injuries in various sports, including soccer, American football, rugby union, Australian rules football, cricket, and sprinting. Epidemiological studies have highlighted the significant loss of training and competition time associated with HSIs, with a typical 25-player soccer squad experiencing 5-6 hamstring injuries per season, each resulting in approximately 14 days of absence. Despite extensive research into injury risk factors, rehabilitation, and mitigation techniques, the incidence of hamstring injuries continues to rise, particularly in men's elite European professional soccer. Research has indicated that exercises like the Nordic hamstring exercise (NHE) can reduce HSI incidence, though this claim has been debated due to methodological discrepancies. Compliance with injury prevention programmes is crucial, with higher compliance rates leading to greater success in reducing HSI rates. Despite the potential benefits of evidence-based prevention programmes, adherence remains a challenge, particularly with high-volume training. The results of recent studies indicate that lower volume NHE programmes can be effective, indicating the feasibility of incorporating such exercises into athletic training schedules. Given the limitations of single-exercise interventions, there is a need for research into more comprehensive training programmes that combine resistance training with high-speed running (HSR) to effectively reduce HSI risk and enhance athletic performance. The overarching aim of this thesis was to inform exercise selection, athlete assessment, and training practices to mitigate HSI risk and improve athletic performance, reflecting the applied practices of strength and conditioning, injury rehabilitation and sport science practitioners.

This research investigated hamstring training practices and perceptions for injury prevention and athletic performance enhancement through both quantitative and qualitative analyses. Chapter 3 utilised a mixed-methods survey to gather data from sport and exercise practitioners across various sports, exploring their training methods, including HSR and approaches to resistance training. The survey revealed significant disparities in training practices, highlighting the influence of educational background, professional role, and multi-disciplinary team (MDT) dynamics. It emphasised the importance of practitioner education, effective communication within MDTs, and developing evidence-informed training practices tailored to sport-specific demands and athlete characteristics.

Building on these findings, Chapter 4 expanded through semi-structured interviews with twelve practitioners, providing a deeper qualitative understanding of nuanced approaches to hamstring training. It explored the rationale behind training decisions, the challenges practitioners faced, and strategies employed to enhance athlete compliance and engagement. Key themes included micro-dosing of the NHE, integrating hip hinge exercises like Romanian deadlifts (RDL), and applying isometric training during congested fixture periods. The study highlighted the critical role of MDT dynamics and continuous athlete education in effective training interventions.

Together, these chapters highlighted the need for more ecologically valid research including concurrent resistance training with HSR, rather than single exercise interventions. The insights aimed to bridge the gap between research and real-world application, providing a robust foundation for developing effective training strategies to reduce hamstring injury incidence and enhance athletic performance.

Chapter 5 focused on establishing the most appropriate normalisation method for electromyography (EMG) based on within-session reliability and variability of various maximal voluntary isometric contraction (MVIC) methods. The study concluded that the manual resistance method (hip extension) provided a reliable and time-efficient means of normalising EMG data for the hamstring and gluteal muscles, which was then utilised in the exercise comparisons conducted in Chapter 6.

Chapter 6 compared the kinetic and EMG characteristics of the RDL and good morning (GM) exercises. Utilising the established EMG normalisation method from Chapter 5, this chapter aimed to develop a biomechanically robust basis for exercise selection decisions. The findings indicated that while higher absolute loads were lifted during the RDL, both exercises produced comparable joint moments and muscle excitations, indicating that the GM could serve as an alternative hip-hinge exercise requiring lower absolute loads yet potentially yielding similar training adaptations.

Together, these chapters provided a comprehensive understanding of hamstring training practices and the reliability of EMG normalisation methods, informing evidence-based decisions in exercise selection for reducing hamstring injury risk and enhancing athletic performance.

Chapter 7 investigated the reliability and bilateral force asymmetry during the NHE using a NordBord device. The study aimed to quantify knee flexor strength, assess bilateral force asymmetry, and determine the reliability of peak force (PF) and mean force (MF) measures. Nineteen strength-trained male participants performed three maximal NHE trials. Data collection focused on PF, MF, and instantaneous force (IF) throughout the exercise. The study found moderate to excellent reliability for PF across trials, with improved reliability and reduced variability when excluding the first trial. MF, while also showing improvements, demonstrated slightly lower reliability and higher variability than PF. The analysis revealed significant between-limb differences in MF, favouring the right limb, and higher IF in the right limb for most of the exercise duration. These findings indicate that relying solely on PF might mask underlying bilateral force asymmetries, highlighting the importance of including MF and IF measures in assessments. This chapter concluded that monitoring multiple force metrics during the NHE was crucial for accurately identifying bilateral asymmetries and informing targeted training interventions. The insights gained were applied in future exercise comparison and training intervention studies within this thesis.

Finally, Chapter 8 examined the effects of integrating knee flexor-biased (NHE) and hip hinge-biased (RDL) resistance training programmes with concurrent HSR on hamstring strength, sprint performance, jump performance, and lower body strength in academy soccer players. The study addressed the lack of ecological validity in previous research, which often focused on single exercise interventions, by employing a more comprehensive training approach. Thirty-seven participants from a football academy were randomly assigned to one of three groups: NHE, RDL, or control. Over six weeks, all groups engaged in a standardised resistance and HSR training programme, with only the RDL, NHE or reverse lunge (control) differing between programmes. The training aimed to progressively increase load while maintaining consistent volume, with sessions held twice weekly. Pre- and post-intervention assessments included countermovement jumps (CMJ), countermovement rebound jumps (CMJ-R), isometric mid-thigh pull (IMTP), and 20 m sprints.

Results indicated significant improvements in all groups, with the NHE group showing the greatest increase in eccentric knee flexor strength, likely due to the specificity and supramaximal nature of the NHE. Both training interventions experienced significant improvement in 20 m sprint performance. However, both intervention groups and the control group experienced significant improvements in 5 m sprint performance, indicating that the sprint intervention was sufficient to improve 5 m acceleration performance, but addition of either the NHE or RDL is required to significantly improve 20 m sprint performance. The study concluded that combining resistance training with HSR enhanced athletic performance and reduced hamstring injury risk, with each training focus providing distinct benefits. The findings supported the integration of varied resistance training strategies in athlete conditioning programs to optimise performance and injury prevention.

Chapter 1 Introduction

1.1- Originality of the Research

The work presented within the current thesis is, to the best of my knowledge; original. Any work that is has not been originally produced by myself has been appropriately referenced. The body of the research is novel in nature initially through a qualitative analysis of applied practices in training for the mitigation of hamstring strain injury risk and enhanced high-speed running performance. Further, the research presents analysis of the force-time characteristics of the NHE which has not been previously reported in the literature. The research presents a kinematic and kinetic analysis of two commonly utilised hip-hinge focused exercises (Romanian deadlift and good morning), which were highlighted through the survey and practitioner interviews included in the thesis. While aspects of kinetic analysis of some of the exercises included have been previously reported in the literature, the methods used by some authors has been, in places, erroneous or unclear as highlighted in the literature review of this thesis. Finally, the training intervention presented within the current thesis reports the effects of two programmes containing combined exposure to resistance training and high-speed running in a team sport environment for the mitigation of hamstring strain injury risk, jump performance and high-speed running performance which has previously been limited in the scientific literature. The development of more ecological valid training interventions was key, given that the majority of the existing literature is focused on single-exercise interventions, with only Ripley et al. (2023) having reported adaptations to resistance training with either the addition of an additional NHE or sprint-running.

1.2 – Background

Hamstring strain injuries have been reported as the most common non-contact injury in a number of sports including soccer (Ekstrand et al., 2011; Hawkins et al., 2001; Henderson et al., 2009; Woods et al., 2004) ; American football (Feeley et al., 2008) ; rugby union (Brooks et al., 2005a; Brooks et al., 2005b; Brooks et al., 2005c; Brooks et al., 2006); Australian rules football (Bennell et al., 1998; Gabbe et al., 2002; Gabbe et al., 2006; Orchard and Seward, 2002; Orchard et al., 1998; Orchard et al., 2010; Seward et al., 1993); cricket (Orchard et al., 2017) and sprinting (Bennell and Crossley, 1996; Drezner et al., 2005). Epidemiological studies have cited a significant loss of training and competition time associated with HSIs; with a typical 25-player soccer squad expecting to suffer from approximately 5-6 hamstring injuries per season, with each injury resulting in 14.3 days (± 14.9 days) absence from training and competition (Ekstrand et al., 2011). Additionally, there is considerable financial burden in elite level sport of approximately 500,000 euros for a single player injury for one month at the elite European soccer level. However, it must be noted that this financial claim has only been cited from a single interview with the chief operating officer of a soccer club completing regularly in the UEFA Champions League (Ekstrand, 2013) and therefore may vary considerably across levels of soccer competition.

Due to the considerable impacts of HSIs, considerable research has been conducted in recent years into the associated injury risk factors, rehabilitative techniques and techniques aimed at reducing the risk of injury. Despite such a high volume of research, HSI incidence reportedly increased by 4% annually in men's elite European professional soccer between 2001-2015 (Ekstrand et al., 2016). Interestingly, the 2016 Australian Football League injury survey indicated that HSI incidence experienced a steady decrease, on average, from 6.7 new injuries per club in 2007 to 5.2 in 2016 (AFL Doctors Association & AFL Physiotherapists Association, 2016). Despite this apparent decline in new incidence, HSI remains the most common new injury incidence reported across the sport (Saw et al., 2018), accounting for 14.05% of new injuries reported per club, per season .

A systematic review and meta-analysis across 8459 athletes by Van Dyk and colleagues (2016), reported the use of the NHE as a means of reducing the incidence of HSI by up to 51%, which is also supported elsewhere by Soomro et al. (2017). However, the claims of a 51% reduction in injury occurrence being attributed to the NHE alone were refuted by Impellizzeri et al. (2021), due methodological discrepancies in the review by Van Dyk et al. (2019), such as including studies that incorporated more than just the NHE. A further systematic review with meta-analysis by Ripley et al. (2021) highlighted compliance with injury prevention programmes is key, with programmes achieving compliance rates of >75.1% achieving greater success in the reduction of HSI injury rates.

It was reported by Bahr et al. (2015), that evidence-based programmes for the prevention of HSI are not adopted in European Champions League or Norwegian Premier League soccer clubs. It must be highlighted, however, that the evidence-based prevention programme referred to by Bahr et al. (2015), progressed to an extremely high volume up to of 90 NHE repetitions per week. With such as high volume of training, it is not surprising that adherence was found to be poor.

In addition to the systematic review and meta-analysis by Ripley et al. (2021), Cuthbert et al. (2019) also conducted a systematic review and meta-analysis on NHE exercise intervention volume on eccentric knee flexor strength and bicep femoris long head

(BFLH) fascicle length (FL). Cuthbert et al. (2019) observed that lower volume NHE programmes do not negatively affect training adaptations in eccentric knee flexor strength and BFLH FL, compared with higher volume programmes, therefore indicating that a lower volume of NHE training may offer an opportunity to implement the exercise in athletic populations, where typically time availability for resistance training within the training week may be limited.

Currently it is plausible to suggest that resistance training seems beneficial for the reduction of HSI risk factors, however the majority of empirical research in this field is comprised of training interventions that include a single exercise (e.g., the NHE) and therefore lack ecological validity in that it is unlikely that strength and conditioning (S&C) and sports injury practitioners only expose their athletes to single training modalities. Therefore, further research into the effects of more ecologically valid training interventions that include a well-rounded resistance training element combined with HSR are required to develop an understanding of how such training methods may affect markers of HSI risk and / or HSR performance.

1.3 – Aims of the Thesis

The overarching aim of the current thesis is to inform exercise selection principles, athlete assessment, and training practices for mitigating HSI risk factors and improving markers of athletic performance. This will be done in a way that reflects the applied practices commonly adopted by strength and conditioning practitioners. To better promote the ecological validity of HSI risk and athletic performance-focused research, it is important to move beyond single exercise interventions, such as the NHE, and establish adaptations to concurrent resistance and HSR-based training.

Furthermore, while interventions such as the NHE are valued by practitioners, many perceive exercises that include the hip hinge as cornerstones in their programme design. Currently, little empirical evidence is available regarding whether differences in adaptation occur between interventions that include either an NHE or hip-hinge focus.

Therefore, the current thesis aims to:

(1) Clearly establish the practices and perceptions of hamstring-focused training to develop an ecologically valid framework for training interventions.

(2) Develop an understanding of exercise selection principles for commonly used hip-hinge exercises beyond EMG-based exercise selection alone.

(3) Investigate the reliability and force-time characteristics of the NHE as a commonly utilised method of assessing knee flexor strength.

(4) Investigate the effects of combined resistance and HSR-based training with either an NHE or hip-hinge focus in academy-level soccer players.

Chapter 2 Literature Review

2.1 Introduction to Chapter

The literature review includes a detailed overview of the existing literature relating to (2.2) epidemiology of HSI; (2.3) mechanisms of HSI; (2.4) risk factors for HSI and (2.5) hamstring specific training interventions.

2.2 – Epidemiology of Hamstring Strain Injury

HSIs have been shown to be the most frequently occurring non-contact muscle injury across a range of sports (Dalton et al., 2015) with overall injury rates of 1.2 – 4.0 injuries per 1000 hours of athlete exposures to training or competition (Ekstrand et al., 2001; Hagel, 2005; Murphy et al., 2016). Additionally, reoccurrence rates have been shown to be high (12-34%, Sherry and Best, 2004) with an elevated likelihood of re-injury occurring within the first two weeks after returning to sporting participation (Orchard et al., 2002), Such re-injury statistics may raise questions as to whether athletes are returning to play too soon, or that rehabilitation stimuli may be insufficient to adequately prepare the athlete for the demands of sporting competition.

One particularly widely cited study by Ekstrand et al. (2016) indicated that HSIs increased on average by 4% per year between the periods of 2001 - 2015 in elite-level European soccer. On the other hand, the 2016 AFL doctor's survey (AFL Doctors Association, 2016) indicated that there was potentially a small reduction in the number of HSIs in the AFL between 2007 - 2016, which raised the question as to whether the continued enhancement of scientific evidence in the field of training for the mitigation for HSI risk was starting to lead to a positive change in injury incidence rates. Furthermore, an alarming claim (Ekstrand, 2013) of the average HSI costing around €500,000 in salaries paid by ban elite-level European soccer club to injured players has been widely quoted to highlight the substantial financial cost of HSIs in applied sport. However, it must be noted here that this figure was taken from an interview with one senior executive at a single UEFA Champions League club and therefore may vary significantly across levels of soccer participation and more significantly still in other sports and the non-elite level.

However, the financial burden and substantial loss of time from sports participation due to common injuries like HSIs have made reducing injury occurrences a shared goal among athletes, athletic development practitioners, and sporting executives. Recently, Howden Insurance Broker's Ltd commissioned the Howden Sport and Entertainment 2021-22 European Football Injury Index (Howden Broking Group Limited, 2022), that presented a detailed breakdown of injuries by type and estimated injury costs by salary across all clubs in Europe's top leagues (English Premier, German Bundesliga, Spanish La Liga, French League 1 and Italian Serie A). A breakdown of HSIs, average cost per HSI and total cost of HSIs in the 2021-22 season is presented in TABLE 2-1.

As can be observed from the data presented in TABLE 2-1, it seems that the widely quoted average cost of €500,000 for a player injury for one month in elite European soccer, is likely an overestimation (which also seems consistent across non-HSIs reported in the 2021-22 football injury index), yet still represents an average cost of €200,000 (± 54,037) per HSI and a total cost of over €91m for the 2021-22 season. Furthermore, with a total over 422 total HSIs across 344 players with an average loss of 25.60 (± 3.4) playing / training days it is clear to see that HSIs present a significant challenge to S&C and sports injury practitioners at the elite level. To provide some additional context here, HSI (422 total occurrences) was the second most commonly reported reason for players across the top 5 European leagues to miss one or more days of training or playing, with only Covid-19 (804 total occurrences) ranking as a more common cause for time loss.

Table 2-1 The number of HSIs, average time lost to injury, total injury occurrence, average and total injury costs across Europe's top five soccer leagues. All monetary values are displayed in Euros, with values from the English Premier League presented using a conversion rate of £1.00 = €1.19 and are expressed in millions (m). All data are adapted from the Howden Sports and Entertainment 2021-22 European Football Injury Index. All injury data was provided by XML Sports Feeds with player salary values provided by Sporting Intelligence.

	English Premier League	German Bundesliga	Spanish La Liga	French League 1	Italian Serie A	Mean (±)	Total
Total players with HSI	104	27	87	41	85	68.80 (33.0)	344
Average Severity (days)	29.35	22.29	21.74	27.19	27.42	25.60 (3.4)	-
Total Injury Incidence	123	31	120	47	101	84.40 (42.7)	422
Average Injury Cost (€)	0.30 m	0.14 m	0.20 m	0.19 m	0.17 m	0.20 m (0.05)	-
Total Injury Cost Across League (€)	36.83 m	4.41 m	23.60 m	9.08 m	17.34 m	18.25 m (12.8)	91.26 m

Another notable observation from the data presented in TABLE 2-1 is that the German Bundesliga reported a much lower number of total HSIs (31), compared with the likes of the English Premier League (123), Spanish La Liga (120), and Italian Serie A (101). While the lower number of HSIs in the German Bundesliga may be partly explained by only 18 teams competing in that league, compared with 20 teams in each of the other four leagues, it seems unlikely that a reduction of four league games per club per season would explain such a large difference in number of HSIs. Some of the lower HSI rates in Germany may be explained by the 4-week winter break during that season between December 21st, 2021 – January 17th, 2022. Whereas La Liga, (5 days), Serie A (10 days) and League 1 (13 days) also had winter breaks, these were to a much lesser extent that in Germany. The English Premier League on the other hand, did have a ‘player break’ which was staggered across three weekends to allow each team two fixture-free weekends in February while still maintaining some league matches on those weekends. However, while England’s ‘player break’ was later in the season than the other top leagues, the English Premier League did suffer a large number of match postponements during December 2021 due to the Omicron variant of Covid-19, meaning that many fixtures were rescheduled into an already congested 2022 calendar which may have negated the potentially positive impacts of the ‘player break’ on overall injury incidence across the season. Due to factors such as rearranged fixtures due to Covid-19 match postponements, players may have experienced acute spikes in total HSR volumes in these congested fixture periods. Research by Duhig et al. (2016) has indicated that acute spikes in HSR demands above and individual’s two-year average may be indicative of an increased risk of HSI.

While factors such as fixture congestion, in-season breaks and total number of games that may contribute to the total volume of HSIs suffered within a season, there are other factors that may also contribute. For instance, total volume of high-speed running and total running volume may differ in the Bundesliga and French League 1 compared with other leagues. Directly comparable data in terms of total running, HSR and sprint running demands across leagues is lacking, although studies such as those of Altmann et al. (2021) and Allen et al. (2023) can be used to draw comparisons between the running demands between leagues. One may assume that one of the key factors that may influence the higher HSI rates in the English Premier League could be attributed to the match-demands compared with other leagues, particularly with the English Premier League often anecdotally referred to in the media as one of the most intense leagues in the world. One may therefore assume that the match-play demands would be higher in the English Premier League than in leagues such as the German

Bundesliga, which may explain the higher injury rates. However, data from Altmann et al. (2021) and Allen et al. (2023) may be in direct contrast to this notion. Match-play demands across positions and as an average across positions are presented in TABLE 2-2. Direct positional comparisons may be difficult given the differences in position definitions in the two studies, for instance Altmann et al. (2021) referred to full backs as a single position, whereas Allen et al. (2023) split this position into wide defenders and wing backs. Similarly, Altmann et al. (2021) separated centre midfield players and defensive midfielders into separate groups, whereas Allen et al. (2023) only considered centre midfield players. However, when considering the averages across all playing positions, the data indicates that while the total running distances between the two leagues may be only small (*d* = 0.44), the HSR and sprint running demands may actually be higher in the German Bundesliga than in the English Premier League with large and moderate effect sizes, respectively (*d* = 1.53 and 1.07). However, it must be noted here that the thresholds used to differentiate between HSR, and sprint running were 5.5 – 7.0 $m \cdot s^{-1}$ and >7.0 $m \cdot s^{-1}$ in the study of Allen et al. (2023), and 4.72 – 6.66 $m \cdot s^{-1}$ and >6.66 $m \cdot s^{-1}$ in Altmann et al. (2021). As a result, it is possible that the true differences in sprint running may be lower than what is reported in TABLE 2-2, given that some of the distances classified as sprint running by Altmann et al. (2021) would be classed as HSR by Allen et al. (2023).

Table 2-2 The total running distance (TD), high-speed running (HSR) distance, and sprint distances by position and as a mean across the English Premier League in the 2018-19 season (left) and German Bundesliga 2019-20 season (right). Magnitude of difference across running actions are presented as Cohen's d as difference in means divided by the pooled standard deviation of the means. Data are adapted from Altmann et al. (2021) and Allen et al. (2023). CB – centre back, FB – full back; DM – defensive midfield; CM – centre midfield; AM – attacking midfield; WM – wide midfield; FC – centre forward; CD – central defence; WD – wide defence; WB – wing back; FW – forward.

	English Premier League 2018-19				German Bundesliga 2019-20				
	Position	Action	Mean (m)	SD (m)	Position	Action	Mean (m)	SD (m)	
		TD	9516	647		TD	10210.0	640.0	
	CB	HSR	572	151	CD	HSR	1040.0	410.0	
		Sprint	121	63		Sprint	190.0	80.0	
		TD	10362	678		TD	10750.0	560.0	
	FB	HSR	1008	241	WD	HSR	1370.0	230.0	
		Sprint	253	104		Sprint	360.0	140.0	
		TD	11291	667		TD	10960.0	550.0	
	DM	HSR	795	245	WB	HSR	1480.0	270.0	
		Sprint	124	80		Sprint	370.0	110.0	
		TD	11429	701		TD	11660.0	920.0	
Position	CM	HSR	877	262	CM	HSR	1570.0	830.0	
		Sprint	144	91		Sprint	240.0	130.0	
		TD	10880	749		TD	11070.0	730.0	
	AM	HSR	1053	230	WM	HSR	1510.0	280.0	
		Sprint	235	110		Sprint	420.0	140.0	
		TD	10522	738		TD	10860.0	800.0	
	WM	HSR	1127	224	FW	HSR	1430.0	300.0	
		Sprint	292	120		Sprint	340.0	130.0	
		TD	10262	786					
	CF	HSR	964	254					
		Sprint	240	120					Cohen's *d*
		TD	10608.9	709.4		TD	10918.3	700.0	0.44
Average		HSR	913.7	229.6		HSR	1400.0	386.7	1.53
		Sprint	201.3	98.3		Sprint	320.0	121.7	1.07

As the above running demand comparison is only for two discrete seasons, it is possible that the running demands alone do not explain the reasons for lower HSI incidence in the German Bundesliga compared to the English Premier League. There it must be considered whether different player management strategies are being used in German football, which perhaps are not adopted in other geographical locations. While the multifactorial risk factors for HSIs are discussed in CHAPTER 2.4, it must also be noted here that it is currently unknown if there were more players that had suffered a previous HSI in the non-German leagues, which given that previous HSI is one of the primary risk factors for future injury may also have played a key role.

Howden's Insurance Brokers (Howden Broking Group Limited, 2023) also published a 2022-23 injury audit, which although less detailed in terms of statistics pertaining to HSIs, the audit did include the time-period in which the 2022 FIFA World Cup took place. The scheduling of the 2022 FIFA World Cup presented a significant scheduling change, given that for players in the top 5 domestic leagues in Europe, the World Cup typically takes place during the summer months, when the domestic season has ended. The 2022 World Cup took place in November-December, during the season for the top 5 European domestic leagues. What was interesting here was that although the total number of players suffering HSIs in Europe's top 5 leagues decreased in from 344 in 2021-22, to 282 in 2022-23, the average number of days missed due to injury increased from 25.6 day to 28.6. The average cost per HSI also increased from €200,000 to €280,000 with an increase in the total cost of HSIs from €91.26m to €104.29m.

As previously stated, Ekstrand et al. (2016) reported that HSIs increased by an average of 4% each season between the 2001/02 and 2013/14 seasons. However, a notable finding from that observation was that HSIs sustained during match-play remained relatively consistent over the time-period, while it was training-related HSIs that increased by 4% annually. Interestingly, an updated UEFA Elite Club Injury study was published covering 21 (2001/02 – 2021/22) consecutive elite European football (UEFA Champions League) seasons including 54 elite teams. The authors stated that over the entire 21 season time-period, players were almost ten times more likely to suffer a HSI during match-play than during training (4.99/1000hours vs 0.52/1000hours; RR 9.67, 95% CI 8.93 - 10.47). Furthermore, over the entire 21 season time-period the authors also reported a significant increase in both training (6.7%, 95% CI 1.7 to 12.5, p = 0.009) and match-play (3.9%, 95% CI 0.1 – 7.0, p = 0.045). One may expect an increase in overall injury incidence with the increase in total number of games in more recent years (e.g., the addition of additional qualifying rounds for the UEFA Champions League and Europa League; more recent additions of post-season tours; addition of extra competitions into the annual schedule such as the UEFA Nations League, with further additional expansions of the Champions League from 32 teams to 36 teams planned for 2024), as well as an increase in player HSR velocities, total number of match-play HSR efforts and total HSR distances covered in matches (Bush et al., 2015). However, an interesting observation from Ekstrand et al. (2016) was that while HSI incidence significantly increased over the 21 seasons, there was no significant (0.7%, 95% CI -0.6 – 1.9, $p \geq 0.05$) increase in overall football injury incidence, indicating that HSIs are unique in that they are a key area of growing concern for sports injury practitioners.

Additionally, the elite club Injury study (Ekstrand et al., 2016) also reported that recurrences made up 18% (475 total) of HSIs during the 21-season period, with recurrences within the first 2-months following the initial injury making up 69% (325 total) of all recurrent HSIs. Additional support for a high potential for recurrence of HSIs in the early stages of return to sport can be found from the study of Orchard et al. (2002) that reported injury occurrence across a 22-week AFL season, reporting a HSI recurrence rate of 12.6% in the first week and 8.1% in the second week following return to sport.

While substantial evidence exists to highlight the impact of HSIs in elite-level men's soccer, studies such as those by Dalton et al. (2015) and Boltz et al. (2022) highlight that HSIs pose a challenge to practitioners in a variety of sports at the Collegiate level. Dalton et al. (2015) investigated the epidemiology of HSIs in 25 National Collegiate Athletic Association (NCAA) sports between the 2009-10 to 2013-14 academic years. Dalton et al. (2015) reported that during that period, a total of 1,142 HSIs were reported, with men's football (403 HSIs; RR 2.80; 95% CI 2.22-3.53), men's soccer (113 HSIs; RR 2.93; 95% CI 2.02 – 4.25), women's soccer (95 HSIs; RR 2.18; 95% CI 1.45 – 3.29), men's indoor track (74 HSIs; RR 6.06; 95% CI 3.12 – 11.78), men's lacrosse (59 HSIs; RR 1.85; 95% CI 1.04 – 3.29), women's lacrosse (33 HSIs; RR 2.06; 95% CI 1.00 – 4.24) and men's baseball (55 HSIs; RR 2.01; 95% CI 1.18 – 3.42) as the sports most associated with HSIs,

Boltz et al. (2022) published a similar epidemiological study into HSIs in the NCAA between the 2014-15 – 2018-19 academic years and found an increase in the total number of HSIs of 1,142 reported by Dalton et al. (2015) to 2,096. Boltz et al. (2022) reported that HSI rates were highest in men's soccer (5.97 injuries per 10,000 athlete exposures [AEs]), followed by men's football (4.35 per 10,000 AEs), and men's track and field (3.57 per 10,000 AEs). In women's sports, HSI rates were also highest in soccer (3.13 per 10,000 AEs), followed by field hockey (2.09 per 10,000 AEs) and track and field (1.98 per 10,000 AEs).

It is widely reported that the BFLH is the most commonly injured of the hamstring muscle group. The number of HSIs that affect the bicep femoris (not all studies have differentiated between the long and short heads of the muscle), varies between 53% and 83% (Woods et al., 2004; Ekstrand et al., 2012; Askling et al., 2013). Additionally, it has been suggested (Askling et al., 2013) that injuries affecting the bicep femoris differ in mechanism compared to those that affect either the semitendinosus (ST) or semimembranosus (SM).

Therefore, while it is clear that HSIs are of considerable burden to athletes and practitioners alike, to better understand the epidemiological data a critical review of the literature in relation to injury mechanisms is warranted.

2.3 – Mechanisms of Hamstring Strain Injury

Researchers such as Askling et al. (2016) have previously suggested that HSIs occur through one of two mechanisms, classified as either stretch-related and HSR-related. It was widely stated that HSR-related HSIs typically occur during the late swing phase of the HSR gait cycle (Danielsson et al., 2020). However, in earlier works by the likes of Mann and Sprague (1980), there were suggestions that injury may occur during the early stance phase of HSR gait.

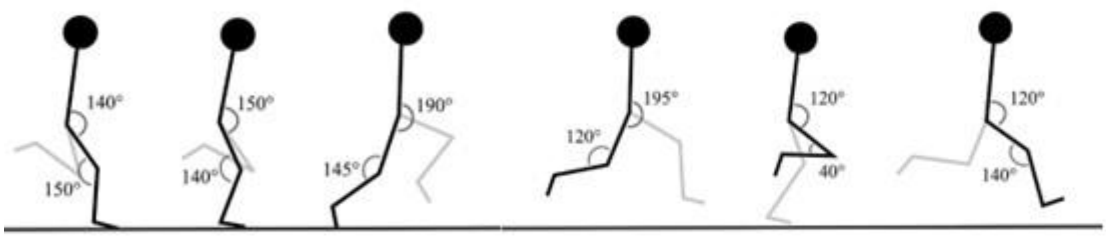


Figure 2-1 Individual subphases of the HSR gait cycle adapted from Kenneally-Dabrowski et al. (2019). The subphases are defined as follows: (from left to right) foot strike; mid-stance; toe-off; early-swing; mid-swing and late-swing.

To investigate the actions of the hamstring muscles during the HSR cycle, Chumanov et al. (2011) conducted a series of computational simulations using three-dimensional running kinematics and sEMG with subsequent forward dynamic simulation of musculotendon work on 12 (9 male, 3 female) participants at five running speeds progressing from 80% through to 100% (peak velocity male 8.0 $m \cdot s^{-1}$; female 7.1 $m \cdot s^{-1}$) of maximal velocity on an instrumented treadmill. It was reported that the hamstring muscles lengthened between 50-90% of the running cycle (0-20% identified as the stance phase, with 21-100% identified as the swing phase), with negative work (indicating eccentric muscle action) between 50-90% of the cycle, before a switch to positive work (indicating concentric contraction) between 90-100%. The notion of eccentric lengthening during the swing phase has also been supported elsewhere (Hay, 1999; Thelen et al., 2005; Wood, 1988), however Yu et al. (2008) also reported a second lengthening period during the late stance phase. Additionally, it was reported that both net positive and negative work by the hamstring increased significantly with velocity, however the net negative work increased at a higher rate than positive work. This may indicate that eccentric loading of the hamstrings increases at near maximal and maximal running velocities to a greater extent than concentric loading which may be one key reason as to why HSIs are thought to occur during the late swing phase of HSR.

Chumanov et al. (2011) highlights that there is likely a need to further sub-categorise the final 10% of the HSR gait cycle into the late-swing and terminal swing phases, given that the that the net joint powers switch from negative work to positive work between 90-100% of the cycle. This finding may offer some support to the notion that HSIs are more likely to occur during the late swing phase of HSR, rather than the terminal swing or stance phases, given that the net positive work by all hamstring muscles during those phases would indicate a concentric muscle action and therefore unlikely to be associated with sarcomere strain. Peak swing phase force was significantly higher in the BF ($p \leq 0.05$; $d = 0.93$ at 100% maximum velocity) than in the stance phase, as was the case in the SM ($p \leq 0.05$; $d = 3.93$ at 100% maximum velocity), however there was no significant differences between phases in the ST ($p \geq 0.05$; $d = 0.16$). However, an additional observation can be made from the computations of Chumanov et al. (2011) in that peak swing phase force was significantly higher in the SM compared with the BF ($p \leq 0.05$; $d = 3.97$). Given that swing phase forces were significantly higher with a very large magnitude in the SM compared to the BF it seems unlikely that musculotendinous forces during HSR alone explain why the BF is more frequently injured during HSR than the BF. Additionally, Chumanov et al. (2011) reported that peak musculotendinous stretch between the BF and SM was not significantly different. On the other hand, Thelen et al. (2005) also reported muscle-tendon unit (MTU) length estimations during treadmill sprinting and found normalised BF lengthening during the swing phase to be significantly ($p \leq 0.01$) higher than in the ST and SM (9.5%, 8.1% and 7.4% of upright standing length, respectively).

With regards to claims that HSIs may occur during the stance phase of HSR as suggested by Yu et al. (2008) and Mann and Sprague (1980), it would seem appropriate here to provide some context as to why this may seem a less likely, although not impossible, position for strain injury to occur. While Yu et al. (2008) suggested the potential of a second lengthening phase in the hamstrings during the latter stages of the stance phase of HSR, it should be noted here that muscle-tendon lengths are a product of joint kinematics, specifically the hip and knee joint in the case of the biarticular hamstring group. In the case of the swing phase of HSR, the hip joint flexes as the knee joint simultaneously extends, leading to hamstring lengthening (Chumanov et al., 2011). However, at or potentially just before, foot contact the hip starts to extend and continues to extend throughout the stance phase whereas the knee flexes up to approximately mid-stance before extending through to toe-off (Kenneally-Dabrowski et al., 2019). Therefore, for a hamstring stretch to occur during the latter half of the stance phase, lengthening due to knee extension would have to exceed shortening due to hip extension, which seems unlikely given that hamstring moment arms at the hip (peak proximal hamstring moments of 0.05 - 0.07 m) are larger than at the knee (peak distal hamstring moment arms; 0.03 – 0.05 m) during HSR (Thelen et al., 2005).

A further factor which requires consideration in the debate as to whether HSIs are more likely to occur during the stance or swing phase of HSR is that of muscle excitation. Several authors have reported that the amount of muscle strain required to lead to a strain injury is lower when the muscle is in a state of higher muscle excitation (and that the amount of strain required to lead to strain injury is higher in states of lower muscle excitation). Yu et al. (2008) reported that although MTU length was not significantly different between the stance and swing phases, muscle excitations in the hamstring were significantly higher during the swing phase of HSR, which is also consistent with Chumanov et al. (2011) Therefore, given the similar MTU lengths during stance and swing reported by Yu et al. (2008) but the higher muscle excitations in the swing phase reported by both Yu et al. (2008) and Chumanov et al. (2011) with the addition of a higher net negative working during the late swing phase and kinematic characteristics of the hip and knee joints, it seems more likely that HSIs suffered during HSR occur during the late, but not necessarily terminal swing phase of HSR, which is also supported by a recent systematic review and meta-analysis on HSI mechanisms (Danielsson et al., 2020).

Van Hooren and Bosch (2016a, 2016b) postulated that there is no eccentric muscle action of the hamstrings during the late swing phase of HSR and that muscle actions were likely to be isometric in nature. The authors then went on to argue that the increase in distance between the proximal and distal hamstring muscle attachments is due to elongation of the series elastic component of the MTU. However, the primary basis for the argument presented by Van Hooren and Bosch (2016a, 2016b) was based on animal studies including quadrupedal animals such as dogs or amphibians such as bull frogs (which do not run). While such studies using non-human species can provide valuable theoretical insights into how MTUs may behave during dynamic actions, it is not known to what extent MTU behaviour may differ in bipedal species. One of the more compelling aspects of the argument put forward by Van Hooren and Bosch (2016a, 2016b) was in relation to behaviour of the contractile and series elastic components of the MTU separately. The notion that the increase in distance between the hamstring MTU attachment points could be explained by elongation of the series elastic component was based on the computational modelling of Thelen et al. (2005). Thelen et al. (2005) simulated MTU dynamics in a three-dimensional Hill-type (Hill, 1938) MTU actuators and a computed muscle control algorithm. From their simulations Thelen et al. (2005) reported that as tendon compliance increased (reduced tendon stiffness), muscle fibre strain decreased, leading to an enhanced storage of energy in the tendon and reduced negative work by the muscle. A potential flaw in the reasoning of Van Hooren and Bosch (2016a, 2016b) that the findings of Thelen et al. (2005) demonstrated a clear rationale that MTU lengthening is mostly explained by tendon stretch is that tendon compliance has been shown to be non-uniform (Lieber et al.,

2002) and tendon shortening has been shown (Pappas et al., 2002) to be non-uniform during muscle contractions. As the simulation used by Thelen et al (2005) assumed uniform MTU properties, it cannot be directly assumed that tendon stretch does occur in the way described by Thelen et al. (2005).

Results of a previous study indicated that tendon compliance may decrease under fatigued conditions, albeit in rabbits (Butterfield and Herzog, 2005). Therefore, if this occurs in humans, then the findings of Thelen et al. (2005) may indicate that HSI injury risk increases under fatigue if increased tendon compliance does increase muscle fibre strain. This increase in tendon compliance under fatigue may also explain previous claims that HSIs are more prevalent in the last 15-minutes of each half in soccer (Ekstrand et al. 2022). However, such reports of a link between increased tendon compliance leading to increased muscle fibre strain during HSR, may also explain why sports that require high numbers of HSR and sprint running actions are inherently linked with high risk of HSI. Given that HSR and sprint running are associated with stretch-shortening cycle actions (Thelen et al., 2005; Chumanov et al., 2007), they can be classed as plyometric in nature. Results of a recent meta-analysis (Ramírez-delaCruz et al., 2022) show that plyometric training can lead to adaptations in increased tendon stiffness. This could mean that frequent exposure to HSR and sprint running could lead to increases in tendon stiffness, thereby increasing muscle fibre strain during HSR and sprint running. This potential inherent risk of HSR and sprint running actions likely highlights the importance of developing high levels of hamstring muscle strength, in both isometric and eccentric contraction modes in order to protect against muscle fibre strain, given that said strain seems to have the potential to be isometric in nature with increased tendon stretch in more compliant tendons and more eccentric in nature with less compliant tendons.

To a lesser degree, HSIs have also been reported to occur during ‘over-stretch’ mechanisms, which include a flexed hip and fully- or hyper-extended knee joint, proposed to occur during actions such as kicking a ball (Hagel et al., 2005), bending forward to pick up a ball from the floor during running (Worth, 1969), during dance (Askling et al., 2007) or in water skiing when getting up onto the skis from a submerged position or following a fall (Sallay et al., 1996). However, in a systematic review and meta-analysis, Danielsson et al. (2020) found only three published studies (Askling et al., 2007; Askling et al., 2008 Sallay et al., 1996) focused on stetch-type mechanisms of HSI, that met the inclusion criteria for review. Of these three studies, none observed the injury mechanism in real-time and relied only on patient reported mechanism of injury, resulted in high risk of bias (scores of 8-11 out of a possible 20) through a modified Downs and Black checklist. Through these three studies, it seems that the most commonly injured muscle during stretch-type mechanisms is the SM, with one study also reporting simultaneous quadratus femoris and adductor magnus strain along with HSI. As there is a relative paucity of evidence in the field of stetch-type injury mechanisms and due to the focus of the current thesis primarily on the mitigation of HSR-based HSIs and training for enhanced HSR performance, stretch-type injury mechanisms will not be discussed at length.

The BFLH is the most commonly injured (Koulouris et al., 2007; Koulouris and Connell, 2003; Verrall et al., 2003) with the proximal muscle-tendon junction (MTJ) being the most frequent location of symptoms and fibre disruption (Askling et al., 2007; Koulouris et al., 2007; Koulouris and Connell, 2003; Verrall et al., 2003). It has not yet been fully established why the majority of BFLH injuries occur at the proximal portion of the muscle-tendon junction (MTJ), however the unique anatomical characteristics of the muscle may explain the phenomenon. An ultrasound (*in vivo*) and cadaver study by Tosovic et al. (2016) indicated that the proximal segment (30% of total muscle length) possesses greater FL (8.05 ± 1.2 cm), greater muscle thickness (MT) (2.72 ± 0.56 cm) and a greater fascicle length-to-muscle length ratio (FL:MT) (0.25 ± 0.03) compared to the distal segment (90% of total muscle length); (FL, 7.06 ± 1.51 cm; MT, 1.37 ± 0.65 cm; FL:MT,0.22 ± 0.05). These anatomical characteristics of the proximal BFLH make it better suited to force generation than the distal segment, which indicates that the proximal portion is under greater loads, particularly during heavy resistance training and high velocity running tasks. However, although one may think that a region of muscle with greater MT and FL, that is conducive to force production may be more resilient to injury, a three-dimensional muscle model created by Rehorn and Blemker (2010), demonstrated non-uniform stretching throughout the BFLH, with the largest degree of muscle stretching localised close to the proximal MTJ. Therefore, it seems that the greater FL alone (and therefore presumably greater number of sarcomeres-in series), alone does not sufficiently protect the proximal BFLH, and although the distal BFLH seems less well equipped against injury, the greater degree of loading at the proximal MTJ, may go some way to explaining the more common injury incidence in that area.

It has been reported that the BFLH proximal aponeurosis is highly variable between participants. It has been previously suggested that a disproportionately small BFLH aponeurosis to muscle cross-sectional area is a risk factor for injury (Fiorentino et al., 2011; Rehorn et al., 2010), indicating that the force producer (muscle), could be much greater than the force transmitter (aponeurosis and tendon), leading to a risk of injury during force transition to the bone. However, Evangelidis et al. (2015), found no relationship between aponeurosis size, muscle size and isometric or eccentric strength.

2.4 – Risk Factors for Hamstring Strain Injury

Aetiology of HSI has been suggested to be multifactorial. Generally, the associated risk factors can be subcategorised into intrinsic modifiable, intrinsic non-modifiable and extrinsic modifiable. Intrinsic modifiable risk factors can be summarised as factors that can be manipulated, for example through training, such as muscle strength. Intrinsic non-modifiable risk factors are those inherent to the individual that cannot be manipulated such as age or previous injury history. Extrinsic modifiable risk factors are those not inherent to the individual that can be manipulated such as high-speed running demands. For brevity, only the intrinsic risk factors will be discussed in detail within the current chapter given that aspects such as high-speed running demands have been covered in the epidemiology subsection of the literature review.

2.4.1 Muscle Strength

It has been suggested that stronger muscles can be more resilient against injury (Suchomel et al., 2016; Lauersen et al., 2014; Lauersen et al., 2018). Given that there is a broad range of strength qualities that can be assessed across an athlete's force-velocity profile, the quality of evidence in relation to muscle strength as a modifiable risk factor for HSI is varied. Broadly speaking, the notion that stronger muscles are more resilient against injury is based on a higher level of force production ability providing a higher ability to withstand muscle strain experienced during activities during which the muscle-tendon unit is forcefully lengthened, such as HSR.

Mechanistically, this is likely associated with the sarcomere popping hypothesis originally proposed by Morgan (1990). Briefly, the sarcomere popping hypothesis indicates that muscle damage occurs from non-uniform lengthening of sarcomeres when the active muscle is stretched beyond its optimum length (relating to the length-tension relationship) (Morgan et al., 2002). Morgan (1990) and Morgan and Proske (2004) suggested that sarcomere stretching beyond optimum length results in the weakest sarcomeres being stretched more rapidly than others, potentially causing deformation of t-tubules, and disrupting calcium ion balance. Although the popping sarcomere hypothesis would be difficult to prove *in-vivo*, numerous studies have been conducted to investigate the relationships between hamstring muscle strength an injury risk or injury occurrence.

A systematic review and meta-analysis by Green et al. (2020) indicated that there was limited evidence that absolute or relative knee flexor strength measured through the NHE, were associated with an elevated risk of HSI (absolute NHE strength SMD=−0.31, 95%CI −0.97 to 0.4, p = 0.13; Relative NHE strength SMD=−0.34, 95%CI −1.1 to 0.4, p = 0.14, respectively). However, the same meta-analysis indicated conflicting evidence in relation to the association with isokinetic knee flexor strength, isokinetic quadricep to hamstring strength ratios and between limb NHE strength asymmetries. Contrastingly, the systematic review and meta-analysis by Rudisill et al. (2023) indicated that from the four studies (Askling et al., 2003; Gabbe et al., 2006; Petersen et al., 2011; van der Horst et al., 2015) that directly measured the effects of eccentric strength training on HSI incidence, there was a reduction in the total number of HSIs by a relative risk ratio of 0.34 (95% CI 0.25 – 0.46). The meta-analysis of Green et al. (2020) did not include the studies of Asking et al. (2003); Petersen et al. (2011) or van der Horst et al. (2015), as those studies did not report changes in specific risk factors associated with HSI (e.g., muscle strength) and only reported injury incidence. It is possible that other factors such as training loads may have contributed to the reductions in overall injury incidence. Therefore, while the reduction in injury incidence cannot be attributed directly to adaptations to the training interventions, it cannot be clearly concluded that eccentric training interventions do not reduce injury incidence even if these effects may not be directly reflected in measurements of risk factor reduction.

It was suggested by Green et al. (2020) that as muscle strength fluctuates, it may not be appropriate to just assess strength as a risk factor based on one single time-point observation (such as baseline testing). Therefore, Green et al. (2020) suggested that regular screening may provide a clearer insight into the associations between strength and HSI risk. Given the recent advancements in accessible technology such as the NordBord and portable force platforms, which use a cloud-based data storage system, large-scale multi-site athlete testing may now be more achievable that it was at the time of studies such as those of Askling et al. (2003), Petersen et al. (2011) and van der Horst et al. (2015). In future, practitioners could pool larger datasets of knee flexor strength along with injury incidence reporting to better establish whether measures of strength from the likes of the NordBord are truly representative of future or recurrent HSI risk.

It is feasible that compliance with and consistency of a training intervention is likely to have an impact on the subsequent adaptations experienced by the participants. One of the key limitations of the systematic reviews and meta-analyses from Green et al. (2020) and Rudisill et al. (2023) is that compliance with or consistency of the reviewed studies was not considered in the analyses. Ripley et al. (2021) conducted a systematic and meta-analysis to specifically investigate the effects of exercise compliance on risk reduction for HSI. In terms of overall impact of training interventions on HSI incidence, there was significant and very large (p = 0.007; Z = 2.70) positive effects favouring the training interventions over the controls. There were large differences between levels of compliance (p = 0.203, Z = −1.272) and consistency (p = 0.137, Z = −1.488), indicating greater effectiveness with increased compliance and consistency, although these effects did not reach the threshold for statistical significance. Additionally, there was a significant and very large (p < 0.001, Z = −4.136) effect for between intervention modality comparisons, with eccentric strength training as being most effective.

It should be noted that the notion of using the NordBord for assessment of eccentric hamstring strength is not without its criticisms. Wiesinger et al. (2019) conducted a critical evaluation of hamstring strength assessment using a custom Nordic hamstring device compared an isokinetic dynamometer. Typically, comparisons between the two methods are difficult because isokinetic assessments are usually conducted in a seated position with the hip in approximately 90° of flexion, resulting in in an increased hamstring muscle length compared to the NHE which completed in ~0° of hip flexion. Wiesinger et al. (2019) therefore controlled for such muscle length differences by utilising a supine lying position during isokinetic assessment. The authors reported 'very poor' correlations (r ≤ 0.58) between the two devices as well as proportional bias towards lower torque values achieved on the IKD compared to the Nordic device (~28%) and high between-device typical error (19%). However, it should be noted that the recommendations for interpreting magnitude of correlation by Hopkins et al. (2009), indicate that r = 0.58 should be interpreted as large. As such the data of Wiesinger et al. (2019) actually indicate large associations between the two methods. Wiesinger et al. (2019) suggested that inter-device torque differences and varied peak torque angles between subjects indicate measurement inconsistencies. The Nordic hamstring device tends to measure lower peak torque angles ($p \leq 0.05$; $g = 2.05$), which may underestimate strength. Additionally, significant torque decrements occur outside the optimal joint angle range. The authors also noted that the minimum detectable change (~15-20%) associated with the Nordic hamstring device could be restrictive when establishing standardised criterion used to identify athletes at higher risk of HSI. For instance, if one was to use the threshold value of 337 N suggested by Timmins et al. (2015), athletes that were as much as 50 N below this threshold value could still be within the boundaries for measurement error. Further, Buchheit et al. (2019) highlighted that potential influence of height and body mass on NHE derived measures of knee flexor strength, which further highlights that such arbitrary threshold values may be unrealistic for smaller athletes and may be achieved much more easily by taller and heavier athletes.

Clearly, there is some debate in the literature with regards to whether eccentric knee flexor strength measured through the NordBord is useful in identifying those at elevated risk of future HSI (Bourne et al., 2015; Opar et al., 2015; van Dyk et al., 2018; Wiesinger et al., 2019). Similarly, debate also exists in relation to assessment of strength made using isokinetic dynamometry. Burigo et al. (2020) conducted a 10-year retrospective cohort study to investigate associations between concentric and eccentric ($60°·s^{-1}$) isokinetic knee flexor strength and HSI risk in professional soccer players in the top two divisions in Brazil. It was reported that a concentric peak torque score below 170.83 N was associated with a significantly higher probability of HSI ($p = 0.0468$; positive likelihood ratio [PLR] = 2.14). Additionally, the authors suggested that in the dominant limb, there was a 2% reduction in injury risk for every one Newton increase in concentric peak torque. On the other hand, the authors did not report any significant association with eccentric knee flexor strength and HSI risk. While the study of Burigo et al. (2020) does provide some potentially useful isokinetic benchmarks for athlete screening, it should be noted that these recommendations were only made on 36 HSIs across the 10-year study period. Similarly, van Dyk et al. (2016) also conducted a longitudinal study (4-year cohort study), investigating the effects of isokinetic strength on HSI risk. In contrast to Burigo et al. (2020), van Dyk et al. (2016) did not report any significant difference in concentric (60°·s^{-1} and 300°·s^{-1}) knee flexor torque (p = 0.15 – 0.43; d = 0.05 – 0.12) in injured players compared to uninjured players, but did report significant, albeit small) reductions in absolute and relative eccentric (60°·s^{-1}) knee flexor torque in those that did suffer HSI compared to those that did not (p = 0.03; d = 0.18 – 0.19). So, while there was contrasting findings from Burigo et al. (2020) and van Dyk et al. (2016), it should be noted that the sample size and total number of HSIs in the study of van Dyk was much larger (563 total participants with 167 HSIs compared to 36 HSIs) than that of Burigo et al. (2020).

On the other hand, Zvijac et al. (2013) conducted a case-control study of first-season National Football League (NFL) players that had been drafted from the first 5 rounds of the previous season's NFL scouting combine. The study included 164 players with 172 HSIs suffered in the first professional season compared to uninjured controls from the same scouting combine. In agreement with van Dyk et al. (2016), Zvijac et al. (2013) found no differences in concentric peak torque between injured and uninjured participants, which may give further substance to the lack of association between concentric isokinetic strength and HSI risk. Zvijac et al. (2013) did not report any eccentric peak torque data for comparison to van Dyk et al. (2016) or Burigo et al. (2020). Additionally, Zvijac et al. (2013) did not report any differences in peak torque or hamstring to quadriceps strength ratios between injured and uninjured players, or between the injured and uninured limbs of the injured players. It is important here to consider that hamstring to quadriceps ratio alone does not take into account absolute strength. Therefore, it is also interesting to note here that the participants in the study of Zvijac et al. (2013) were stronger than what is reported elsewhere. For instance, the 95% CIs of peak knee flexor torques reported by Zvijac et al. (2013) ranged between 183 Nm – 217 Nm, whereas Barrué-Belou et al. (2023) reported mean knee flexor torques of ‘trained’ (albeit non-elite) males of 89.8 ± 21.0 Nm. Further, Śliwowski et al. (2017) reported isokinetic peak knee flexor torques ranging between 133–163 Nm in professional soccer players playing at the highest level in Poland.

A key criticism of the study of Zvijac et al. (2013) is that muscle strength of the hamstrings and quadriceps were assessed during concentric actions. Assessing the associations between concentric hamstring strength and injury occurrence may potentially be lacking in ecological validity, given that the contraction mode of the hamstrings seems to be most likely eccentric during the late swing phase of HSR. For this reason, some other authors have used a ‘functional’ hamstring-to-quadriceps (FHQ) ratio, to investigate associations between hamstring-quadriceps strength ratios but with isokinetic knee flexor torque assessed during an eccentric action and knee extensor torque assessed during a concentric action. However, the assessment of strength ratios derived from eccentric hamstring and concentric quadriceps actions can be further classified into FHQ when using the same movement velocity in both actions and ‘mixed’ hamstring-to-quadriceps strength ratios (mixed HQ) when using unmatched movement velocities in the eccentric and concentric actions.

For instance, Croisier et al. (2008) investigated mixed ratios in professional soccer players in Belgium, Brazil and France (specific level of play not reported). It was found that those players with a mixed HQ ratio of <0.80-0.89 were at an increased risk of

HSI (or equated to <0.45-0.47 for a concentric-only ratio). It should be noted that the mixed HQ ratios reported by Croisier et al. (2008) were obtained through a concentric knee extension velocity of 240°·s^{-1} and an eccentric knee flexion velocity of 30°·s^{-1}. Although the authors justified their choice of unrequited test velocities due to the previous report by Lossifidou and Baltzopoulos (1996) that the isokinetic period is reduced at high eccentric angular velocities, which may have led to an underestimation of the eccentric peak torque due to peak torque typically occurring towards the end of the movement (closer to full extension), it is not clear how much these ratios would be affected if they were established using the FHQ method.

Interestingly, the systematic review by Baroni et al. (2020) reported average concentric HQ ratios in soccer players obtained at low (12-60°·s^{-1}) and intermediate (90-180°·s^{-1}) angular velocities ranged between 0.50-0.71 and 0.51-0.80, respectively and ranged between 0.50-0.89 at high angular velocities (240-500°·s^{-1}). From these concentric ratio ranges, there seems to be considerable overlap across average scores between test velocities. Therefore, it seems understandable as to why it may be difficult to establish a clear threshold at which athletes may be considered at high risk for HSI. It should also be noted that the conventional HQ ratio thresholds for higher risk of <0.45-0.47 proposed by Croisier et al. (2008) do represent ratio values that are below the averages reported by Baroni et al. (2020), which may offer some substance to the argument that conventional HQ ratios that are below average may be indicative of elevated risk of HSI in soccer players. However, Baroni et al. (2020), Reeves et al. (2005) and Reeves et al. (2009) have all reported that muscle strength capacity decreases exponentially at increasing shortening velocities, eccentric peak torque seems to remain unchanged with faster active stretching of the muscles. These observations may be key when selecting methods of establishing HQ ratio as while eccentric knee flexor peak torques are likely to remain relatively unchanged at low to intermediate test velocities, the concentric knee extensor torque is likely to reduce as test velocity increases, therefore likely making it 'easier' to achieve a higher HQ ratio if a higher knee extension velocity is selected.

More recently, Kellis et al. (2023) conducted a systematic review and meta-analysis to investigate whether the use of HQ ratios (conventional, functional or mixed) is useful in predicting HSIs. The review included 18 studies, reporting 585 HSIs from 2945 participants. Of the 18 studies included, non-significant findings were reported with reference to HQ ratios between the injured and non-injured legs or the injured and non-injured groups in 14 studies. In terms of the specific ratios, similar trends were reported, with 14 of 11 studies indicating non-significant findings for conventional HQ ratios at $60°\cdot s^{-1}$; 5 of 6 studies reporting non-significant findings using FHQ and 4 of 5 studies reporting non-significant findings when using mixed HQ ratios. As a result, it was concluded by Kellis et al. (2023) that HQ ratios offer limited predictive value of HSI risk.

2.4.2 – Muscle Architecture

A muscle's force generating capacity is underpinned by its architectural characteristics including muscle FL, pennation angle (PA), MT and cross-sectional areas (CSA). In particular, the FL of the BFLH has been suggested as a key modifiable risk factor for HSI. The underpinning theory as to why BFLH FL may be a risk factor, relates back to the previously discussed sarcomere popping hypothesis proposed by Morgan (1990). An individual muscle fascicle is made up of numerous sarcomeres in-series and therefore, a longer fascicle is presumed to possess a greater number of sarcomeres in-series. As a muscle actively lengthens (e.g., the hamstrings during the late swing phase of HSR), it is thought that a higher number of sarcomeres can 'share the load' of this forceful lengthening compared to the same lengthening in the presence of fewer in-series sarcomeres. Further, it is thought than an increase in the number of sarcomeres in-series can allow for a greater force generating capacity through the lengthening portion of the length tension relationship (i.e., between points A and B in FIGURE 2-2), potentially leading to a reduced risk of muscle damage.

As with muscle strength, there seems to be a lack of consistency in the literature as to what extent hamstring muscle architecture should be considered as a modifiable risk factor for HSI. Kellis and Sahinis (2022) conducted a systematic review and meta-analysis to investigate differences in hamstring muscle architecture between the previously injured limbs and contralateral limbs in individuals with history of HSI or in previously injured individuals compared with healthy controls. It was concluded that there does not seem to be any differences in hamstring muscle architecture between the previously injured limb and contralateral limb in previously injured athletes BFLH FL (standardised mean difference [SMD] = 0.40; 95% CI 0.93 - 0.1; p >0.05; I^2 = 0.00%), PA (SMD = 0.17; 95% CI 0.44 - 0.78; p > 0.05; I^2 = 54.15%), MT (SMD = 0.31; 95% CI 0.73 - 0.10; p > 0.05; I^2 = 0.00%) or muscle volume (SMD = 0.11; 95% CI 0.51 to 0.29; p > 0.05; I^2 = 0.00%). In contrast, it was found that athletes with previous history of HSI had significantly shorter BFLH FL than the previously uninjured controls (SMD = 0.57; 95%CI 0.92 - 0.22; p = 0.0015; I^2 = 0.00%). However, no significant between group differences were found in PA (SMD = 0.10; 95% CI 0.34 - 0.55; p > 0.05; I^2 = 0.00%) or MT (SMD = 0.39; 95% CI 0.84 - 0.06; p > 0.05; I^2 = 0.00%).

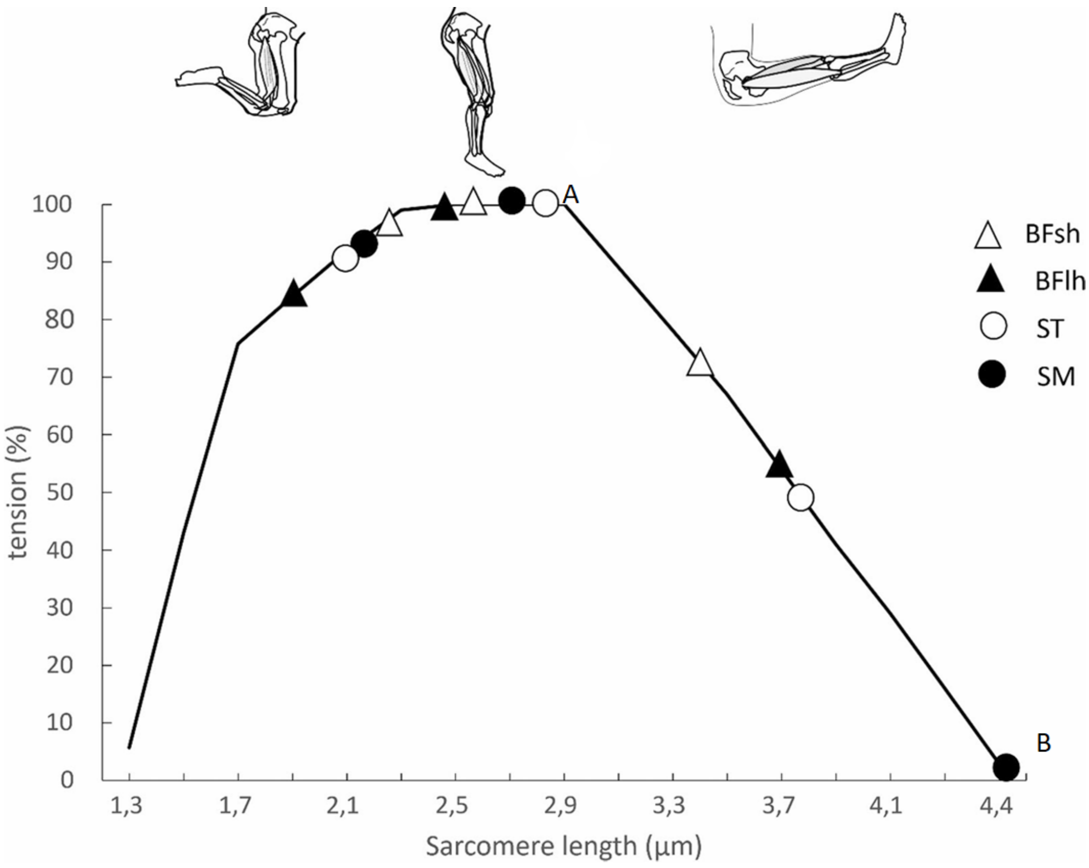


Figure 2-2 Hamstring sarcomere length-tension relationship as a function of hip and knee joint position adapted from Kellis and Blazevich (2022).

The underpinning reasons why previously injured athletes seem to possess different muscle architecture compared to their non-injured counterparts, but not compared to their own uninjured limbs is not entirely clear. Such architectural differences may be due to a lack of evidence that compares muscle architecture pre- and post-injury (Kellis and Sahinis 2022). It could be that the development of scar tissue following injury (Slavotinek et al., 2002) does not affect the size and architecture of the muscle. From the existing muscle architecture literature, it seems that those with a previous history of HSI are likely to possess shorter BFLH FL than those without previous history, which further highlights the likely interaction of risk factors for HIS given that previous injury is one of the strongest predictors of future HSI risk.

2.4.3 – Flexibility

Reduced flexibility has been proposed as a potential modifiable risk factor for injury. As the hamstring muscles experience lengthening during the late swing phase of HSR, it has been claimed that a lack of flexibility in the muscles could contribute to an increased likelihood of muscle damage. Maniar et al. (2016) conducted a systematic review and meta-analysis into hamstring muscle flexibility following HSI. Interestingly, the authors reported that significant and large reductions in hamstring flexibility measured via the passive straight leg raise test were found within 10 days following injury ($p \leq 0.01$; $d = -1.12$; 95% CI −1.76 - −0.48; I^2 81%), but that these effects reduced to moderate and then small between 10-20 days ($p = 0.02$; $d = -0.74$; 95% CI −1.38 - −0.09; I^2 76%) and 20-30 days ($p = 0.03$; $d = -0.40$; 95% CI −0.78 - −0.03; I^2 4%), respectively. At 40 days post-injury, it was reported that there were no significant differences ($p = 0.50$; d = -.012; 95% CI -0.46 – 0.23; I^2 1.82%) in flexibility, indicating that flexibility deficits are likely resolved within the first 40 days following injury. On the other hand, the same authors reported that differences in flexibility measured through the passive knee extension test were not significant at any time-point ($p \geq 0.05$; d = -0.24 – 0.14; I^2 0.0 - 63.2%). The findings of Maniar et al. (2016) may indicate that flexibility tests may be sensitive to hamstring lengthening during simultaneous hip flexion and knee extension (passive straight leg raise) but not to passive knee extension when the hip joint position is fixed (passive knee extension). Contrastingly, the systematic review and meta-analysis of Green et al. (2020) found no clear relationship between hamstring flexibility, mobility or range of motion and risk of HSI through the active or passive knee extension tests, passive straight leg raise or slump tests. However, Green et al. (2020) did report some limited evidence of associations between active knee extension deficits and HSI risk after a return to play.

The findings of Maniar et al. (2016) and Green et al. (2020) indicate that hamstring flexibility should be considered as a criterion during rehabilitation from injury, with 40 days as a realistic timeframe in which to expect restoration of full range of movement. However, due to the retrospective nature of the studies included in the meta-analysis (all participants having suffered HSI), it is not clear whether reductions in flexibility are as of a consequence of injury or were a causative factor in the initial onset of the injury. Additionally, it is not currently known to what extent flexibility interacts with fascicle length as risk factors. For example, it could be the case that shorter fascicles with fewer sarcomeres in-series lead to a reduced lengthening capacity. Alternatively, it could be the case that fascicle length may not affect flexibility and that it could be underpinned by tendon extensibility. Therefore, further research is needed to investigate any potential interaction effect between the two potentially related risk factors.

2.4.4 – Fatigue

It was reported by Woods et al. (2004) that 47% of HSIs suffered in an audit of professional soccer injuries occurred in the final third of each half during match-play. This observation has led to several investigations into the influence of muscle fatigue on HSI risk, given that investigations into animal muscles have shown that the amount of energy required to lead to structural failure of muscle tissue is likely lower under fatigued conditions (Mair et al., 1996). In human participants, studies into the links between muscle fatigue and HSI risk have primarily been in relation to fatigue induced changes in running biomechanics (Piniger et al., 2000), fatigue induced changes in muscle strength (Greig, 2008; Small et al., 2009) or measures of proprioception (Allen et al. 2010). Piniger et al. (2000) investigated the effects of fatigue on 40 m sprint kinematics and reported significant and moderate reductions in knee flexion (p =

0.009; $g = 0.88$) and hip flexion ($p = 0.025$; $g = 0.85$) during the terminal swing phase of running gait. This more extended knee joint position in terminal swing could have increased hamstring lengthening, however the reduction in hip flexion could be a compensatory proprioceptive pattern to offset this increase in muscle lengthening. However, Allen et al. (2010) investigated the effects of fatigue on knee joint position sense and found that under fatigued conditions, participants experienced significant and very large ($p \leq 0.05$; $g = 2.22$) changes in joint position sense, whereby hamstring length was underestimated when in a fatigued state. These observations were made in a seated position on an isokinetic dynamometer; therefore, it is not known whether the results would be replicated during running gait. If similar underestimations of hamstring length were present during running gait, this could lead to potential repeated over striding which may increase HSI risk and have a potential negative impact on HSR and sprint running performance.

Greig (2008) reported significant reductions in isokinetic eccentric knee flexor torque from an intermittent treadmill protocol at $180°\cdot s^{-1}$ and $300°\cdot s^{-1}$ but not at lower angular velocities of $60°\cdot s^{-1}$. These data may indicate that muscle fatigue does potentially reduce force output which could in-turn increase HSI risk. It should be noted that the ICC values reported for the $180°\cdot s^{-1}$ and $300°\cdot s^{-1}$ conditions were only just above (0.76 – 0.78) the threshold of 0.75 for acceptable reliability, which given the recommendations of Koo & Li (2016) that ICCs should be interpreted on the lower bound of the 95% CI, could indicate that the reliability of these higher velocity measures would have fallen below the acceptable levels if interpreted as per the recommendations of Koo & Li. (2016) On the other hand, Small et al. (2009) reported significant and large ($p < 0.01$; *Eta* = 0.672) reductions in eccentric peak flexor torque following 45 minutes and 90 minutes of a simulated soccer protocol.

More recently, Zandbergen et al. (2023) conducted a systematic review and meta-analysis investigating the effects of running-induced fatigue on running kinematics in different experience levels of runner (e.g., novice and experienced). The authors reported significant increases in peak tibial acceleration in response to fatigue (SMD 0.39; 95% CI 0.16 – 0.62; I2 14%). This finding may indicate that if there is a reduction in muscle force production capacity as a result of fatigue, the consequence could be an increase in tibial acceleration that may lead to increases in fascicle lengthening velocity and subsequently increased risk of HSI. Further to this, Evangelidis et al. (2022) investigated the effects of fatigue on mechanical properties of the hamstring muscles and found that during eccentric contractions, the BFLH is fatigued to a greater extent than the other hamstring muscles, which could provide some insight into the higher prevalence of BFLH strains than strains to the medial hamstrings (MH).

2.4.5 – Lumbo-Pelvic Control

Several authors have proposed a lack of lumbo-pelvic control as a risk factor for sustaining HSI (Kalema et al., 2022; Panayi. 2010; Brukner et al., 2014; Sherry and Best, 2004; Mendiguchia et al., 2012). Lumbo-pelvic control refers to the ability to control postural positions of both the lumbar region of the spine and the pelvis (Panayi. 2010; Bramah et al., 2023) and relates to HSI risk given the proximal attachment point of the hamstrings at the ischial tuberosity. Chumanov et al. (2007) modelled the muscles crossing the trunk and pelvis during the swing phase of sprint running and found that the concentric action of the iliopsoas of the stance leg causing anterior pelvic rotation led to an increase of ≥25 mm of BFLH stretch in the swing leg. Given that the BFLH experiences lengthening strain from the simultaneous hip flexion and knee extension during the swing phase of sprint running, it is possible that additional lengthening caused by anterior pelvic rotation could contribute to HSI incidence. In contrast, Chumanov et al. (2007) also reported that the gluteus maximus, adductor magnus and both internal and external oblique muscles all reduced BFLH stretch through resisting anterior pelvic rotation, which may highlight the importance of the agonist-antagonist relationships of the lumbo-pelvic muscles during sprint running. Additionally, a limited number of authors (Brooks et al., 2006; Woods et al., 2004) have reported that possible excessive anterior pelvic tilt observed in some ethnic groups (e.g., black African and Caribbean), which may highlight a further need for development of posterior chain muscle strength in those athlete groups as a means of mitigating potential increases in HSI risk due to anatomical predisposition additional BFLH stretch due to anterior pelvic tilt.

It has been proposed by numerous authors (Bramah et al., 2023; Franettovich Smith et al., 2017.; Schuermans et al., 2017) that muscle excitation may partly explain the link between lumbo-pelvic control and increased HSI risk, however the findings in this area are conflicting. For instance, Franettovich Smith et al. (2017) reported a significantly higher peak and mean gluteus medius excitation when running at 12 and 15 km·h (3.33 and 4.16 $m \cdot s^{-1}$, respectively) and significantly higher mean gluteus maximus excitation at 15 $km \cdot h^{-1}$ in Australian Football players that went on to suffer a HSI. On the other hand, Schuermans et al. (2017) reported lower levels of gluteus maximus, erector spinae and oblique muscle excitation in those that went on to suffer subsequent HSI. While the influence of lumbo-pelvic muscle excitation on HSI occurrence cannot be discounted based on existing evidence, it should be noted that other covariates such as muscle strength or fascicle length were not reported in the studies of Schuermans et al. (2017) or Franettovich Smith et al. (2017), however the authors did not report any significant differences between groups in terms of muscle volume or history of HSI. Further to this, criticisms can be made of the inferences drawn from EMG amplitudes alone. For instance, Schuermans et al. (2017) did report significantly lower excitation in the gluteus maximus and the trunk muscles during the start of the front swing and terminal back swing, respectively, during high-speed running in elite-level soccer players that went on to suffer a HSI in the subsequent 1.5 competitive seasons compared with those that did not suffer HSI. However, Schuermans et al. (2017) did not account for other potentially confounding variables as they did not assess any potential differences in HSR kinematics such as maximal velocity or joint or joint displacements which may have influenced the level of muscle excitation. While Franettovich Smith et al. (2017) did report muscle excitations at set running velocities, neither Franettovich Smith et al. (2017) or Schuermans et al. (2017) assessed differences in muscle strength, architecture, or history of HSI which all could have contributed to why some players suffered HSIs and others did not. Finally, there was no consideration given to match-play or training loads experienced by those that suffered injury, so it is also not possible to establish whether those that suffered injury were exposed to greater HSR volumes, total training loads or acute spikes in training volume-loads around the time of injury. It should also be noted that the running velocities of 3.33 and 4.16 $m \cdot s^{-1}$ used by Franettovich Smith et al. (2017) were below the threshold typically considered as ‘high speed’, therefore it is not clear how accurately these excitations would truly represent muscle excitation during the typical mechanism of injury.

2.4.6 – Previous Injury

In the systematic review and meta-analysis of Green et al. (2020), it was reported that a history of HSI significantly increased risk of future HSI by a relative risk ratio (RR) of 2.7 ($p \leq 0.001$). The risk of future HSI was also reported to increase further if the previous HSI had been suffered within the same competitive season (RR = 4.8; $p \leq$

0.001). These findings are indicative of previous HSI being one of the strongest predictors of future injury risk and likely means that practitioners working with athletes with a history of injury, particularly recent injury, should more closely monitor these athletes and pay particular attention to the modifiable risk factors discussed within this chapter as a means of mitigating the athlete's injury risk as best as possible in the presence of a significant non-modifiable risk for that individual.

The findings of Green et al. (2020) are in agreement with Erickson and Sherry (2017) that suggested that risk HSI injury re-occurrence was highest within the first two weeks following a return to sport. Ekstrand et al. (2011) has previously reported an average loss of 14.3 days (± 14.9) of training following HSI, with more recent reports from the Howden's 2021 injury report of 25.6 days (± 3.4) following HSI. The reports of an increased risk of future HSI following recent injury could further highlight the possible interactions between HSI risk factors. For instance, Maniar et al. (2016) reported that hamstring flexibility is significantly reduced for up to 30 days post-injury, which could indicate that such reductions may be linked with elevated risk of injury within that time-period, which may highlight the importance of ensuring that range of motion is restored prior to a return to training or sport. Furthermore, Kellis and Sahinis (2022) reported that FL was significantly reduced in previously injured athletes compared to those without previous injury history, which may indicate a need to monitor adaptations in fascicle length during rehabilitation.

Finally, it was also reported by Green et al. (2020) that a history of previous anterior cruciate ligament (ACL) injury (RR = 1.7; $p = 0.002$) or calf muscle injury (RR = 1.5; $p \leq 0.001$) also increased risk of future HSI. These reports indicate a need for practitioners to consider the athlete's broader history of injury when establishing risk of future HSI and should likely classify those athletes with previous ACL and calf muscle injury at an elevated risk for future HSI.

2.4.7 – Age

Older age has been suggested as a non-modifiable risk factor for HIS, with Green et al. (2020) reporting a significant increase in injury risk in older individuals from a meta-analysis of 19 studies (SMD = 1.6; 95% CI 0.6 - 2.6; *p* = 0.002). While the threshold at which an athlete would be considered ‘older’ is difficult to establish, it was reported by Green et al. (2020) that the ages of 23 or 24 years seem to be the point at which injury risk increases. It is not clear as to why being over the age of 23-24 years would be a risk factor for injury alone without considering potential covariates. For instance, in European soccer, a typical professional player pathway is through under 18’s squads into under 21 squads, with the likes of the ‘English Premier League 2’ (EPL2) being introduced from the 2016-17 season, although the age group format for the EPL2 being altered from under 23s to under 21s from the 2022-23 season, with similar format of age group leagues being held at lower professional levels and in other European countries. Previous studies have reported lower match-play sprinting demands in academy age groups compared with first-team level in soccer (Morgans et al., 2022; Reynolds et al., 2021) Therefore, younger players are typically exposed to fewer first-team match play scenarios, likely reducing the exposure to higher intensity competition compared with their older counterparts. In the 2019-20 English Premier League season, the average age of a starting 11 was 27.05 years (Smith, 2020), which supports the notion of older players being exposed to more match-play competition. Further to this, the number of total injury incidences by age across the 5 major European soccer leagues can be seen in TABLE 2-3. This data highlights a higher total proportion of injuries in players over 21 years of age (although not all HSIs) but likely highlights a need for future studies to consider match-play exposures as a potential covariate in the investigation of age as a risk factor for injury.

Table 2-3 Total Injury incidences in Europe's top 5 soccer leagues by age group.

	Total Injury Incidences			
League	Under 21	21-25	26-30	Over 30
German Bundesliga	109	412	457	227
English Premier League	73	394	509	255
Spanish La Liga	42	228	333	245
French Ligue 1	65	219	262	145
Italian Serie A	37	264	314	220
Total	326	1517	1875	1092

Opar et al. (2012) conduced a review into the factors which lead to HSI and injury re-occurrence. The authors also reported age above 23-24 years as a key risk factor for HSI. One proposed reason for an increased risk of HSI in older individuals proposed by Opar et al. (2012) was a decrease in muscle strength and muscle mass associated with aging (Gabbe et al., 2006). However, the authors also highlighted that the evidence in support of their theories relating to muscle mass and strength declines did come from participant samples (Doherty, 2001; Kirkendall and Garrett, 1998) which were significantly older than a typical athletic population. As a result, Opar et al. (2012) stated that they felt it unlikely that athletes ages 24-30 would have significantly reduced muscle mass or strength levels compared younger adult athletes.

2.4.8 – Interactions Between HSI Risk Factors

HSI risk is typically considered to multifactorial, however investigations into the likely complex interactions between the risk factors discussed in this chapter is relatively limited. While some authors have investigated potential interactions between risk factors such as muscle strength and muscle architecture, further consideration of the potential interactions between the risk factors discussed here is warranted.

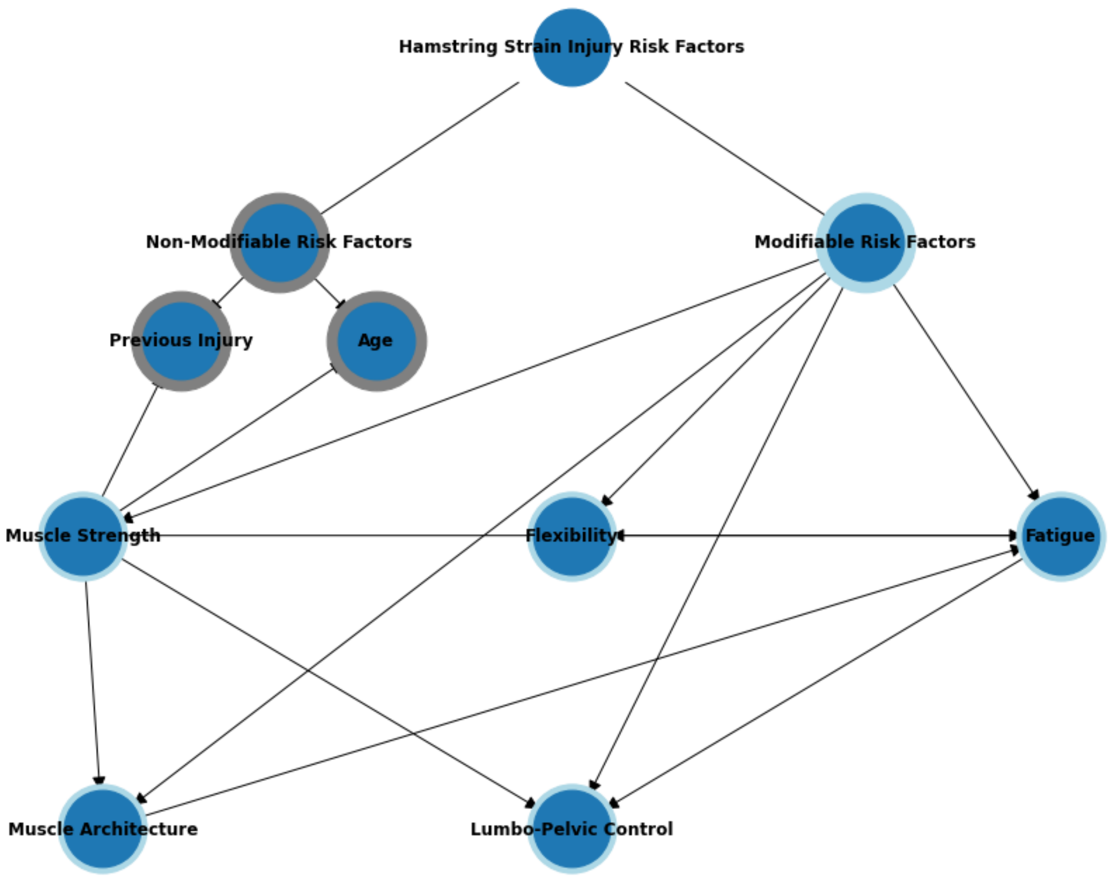


Figure 2-3 Schematic of the potential interactions between modifiable and non-modifiable risk factors for HSI. Modifiable risk factors are represented by blue circles with a light blue circumference, whereas non-modifiable risk factors are represented by blue circles with a grey circumference

The potential interactions between modifiable and non-modifiable risks of HSI are presented in FIGURE 2-3. As previously discussed in the current chapter, the force generating capacity of a muscle is underpinned by the length-tension relationship and as reported by Kellis and Sahinis (2022), as muscle sarcomere length increases, the muscle's ability to generate active tension decreases. Therefore, an interaction may exist between reductions in muscle strength (Green et al., 2020) and fascicle length (Cuthbert et al., 2020). Timmins et al. (2016) proposed the 'quadrant of doom' in which it was recommended that soccer players with absolute knee flexor forces (NordBord derived) of ≤337 N and BFLH FL of ≤10.56 cm were at an increased risk of injury. However, it should be noted that the likes of Buchheit et al. (2019) have highlighted the likelihood of both body mass and height as likely cofounding variables and that normalising force values and muscle architecture to body mass and height, or thigh length may be more appropriate. While shorter muscle fascicles may possess a lower-number of sarcomeres in-series, they are also likely to have a lower force generating capacity which may limit the muscle's ability to withstand the high hip flexor and knee extensor moments associated with HSR. Further to this, a decrease in the flexibility of a muscle is also likely to cause a left shift in the force-tension relationship, resulting in peak force generating capacity to occur at shorter muscle lengths, in-turn reducing the force generating capacity when the hip is flexed, and the knee is close to terminal extension in the late swing-phase of HSR.

However, Wan et al. (2017) investigated relationships between hamstring flexibility (derived from a passive straight leg raise) with isokinetic peak torque and motion capture-derived optimal hamstring muscle lengths. Optimal muscle length was significantly affected by flexibility score (R^2 = 0.535; p = 0.001), but there was no meaningful or significant relationship between peak torque and flexibility (R^2 = 0.006, p = 0.622) or muscle length (R^2 = 0.012, p = 0.505). The findings of Wan et al. (2017) indicate that while there may be a significant interaction between optimal muscle length and flexibility, there may not be a significant interaction between flexibility and strength. On the other hand Alonso et al. (2009) investigated the effects of hamstring flexibility on isometric knee flexion angle-torque relationships and found that although flexibility did not significantly affect peak torque, peak torque occurred in a significantly ($p \leq 0.05$; $g = 0.72 – 0.92$) more flexed knee joint position (i.e., shorter muscle length) in those with reduced flexibility, which may support the hypothesis that reduced flexibility may cause a left-hand shift in the force-tension relationship, resulting in a reduced ability to generate high forces during the late swing phase of HSR.

As stated by Green et al. (2020), athletes with a previous history of HSI are more susceptible to future HSI, which may be due to structural changes in the muscle, meaning that while previous HSI itself is a non-modifiable risk, the consequences of the injury are actually modifiable. For instance, it has been reported that previous injury can result in muscle atrophy (Sanfilippo et al. 2013), development of scar tissue (Silder et al., 2008), reduced muscle FL (Timmins et al., 2016) and reduced muscle excitation (Fyfe et al., 2013). Given that previous HSI has been recommended as likely the strongest predictor of future HSI risk (Green et al., 2020), then it seems that practitioners working with athletes with a history of HSI should monitor changes in these modifiable risk factors along with the restoration and further development of muscle strength beyond the levels of strength that the athlete possessed prior to the injury. Athlete age has also been recommended as one of the strongest predictors of future HSI risk (Green et al., 2020). It has already been discussed in the current chapter that this may be due to a likely increased exposure to training and match-play in older athletes compared with academy-level and younger professionals in sports such as soccer. However, a limitation of the insinuation that older age is a risk factor of future HSI does not take into account that with a longer involvement in sport comes a higher likelihood that the athlete has experienced a HSI in their career, so it is not known to what extent previous HSI influences age as a risk factor.

There is conflicting evidence in relation to an interaction between age and reduced muscle strength in athletic populations. For instance, Jeanguyot et al. (2023) found no significant differences in relative eccentric hamstring strength (NordBord derived) across skeletal age groups of under 13 years of age through to under 18 years of age compared with professional soccer players from the Qatari Stars soccer league. On the other hand, Bourne et al. (2015) reported that under 19 years (18.1 ± 0.8 years) of age Rugby Union players achieved significantly higher relative eccentric hamstring strength values than elite players (24.4 ± 3.1), albeit with a small magnitude ($p \leq 0.05$; $g = 0.48$). These contrasting results do not provide a clear indication of whether age has a truly negative effect of muscle strength in athletic populations, but likely indicates that practitioners should monitor that relative muscle strength does not decline with increasing age.

The presence of neuromuscular fatigue may also interact with other modifiable risk factors of HSI. For instance, Small et al. (2009) reported significant ($p \leq 0.01$; $g = 1.88$) increases in anterior pelvic tilt during a soccer simulation protocol ($SAFT^{90}$), which given the previously discussed suggestions from the likes of Chumanov et al. (2007) that an increase in anterior pelvic tilt may increase BFLH muscle length and suggestions from the likes of Greig (2008) and Small et al. (2009) that fatigue may be associated with a decrease in muscle force generating capacity, may indicate further interaction between risk factors for HSI.

2.5 Hamstring Specific Training Interventions

Several systematic reviews and meta-analyses have reported the standardised effects of training interventions on HSI injury rates or on specific intrinsic-modifiable risk factors such as muscle strength and architecture. Further to this, authors have also investigated a variety of training methods on markers of athletic performance such as sprint running, change of direction ability, and jump performance. The following literature review subsection aims to critically analyse the evidence-base focused on hamstring-specific training interventions for injury risk mitigation and improved athletic performance. The effects of training interventions on injury occurrence is only briefly covered here as to avoid repetition of the earlier literature review subsections which focussed on injury risk factors and highlighted equivocal evidence for the effectiveness of training interventions for meaningful reductions in injury incidence as highlighted by Impellizzeri et al. (2021).

2.5.1 Effects of Training on Muscle Strength

The systematic reviews and meta-analyses of Rudisill et al. (2023); Gérard et al. (2020); Bautista et al. (2021); Muniz Medeiros et al. (2021); and Cuthbert et al. (2019) have all quantified the standardised effects of training interventions on various measures of hamstring muscle strength. The heterogenous nature of the inclusion criteria for these meta-analyses means that the exact studies reviewed by each author group differs as do the key findings. Cuthbert et al. (2019) analysed the effects of NHE training on various measures of hamstring strength and reported trivial-moderate adaptations in relative eccentric peak torque (g = -0.08 – 0.61); with very large positive effects for eccentric peak torque (g = 2.12; 95% CI 1.37 – 2.87); and small – very large positive effects for eccentric force (g = 0.38 – 2.28), with all control groups showing trivial-small changes in strength measures (g = -0.29 – 0.04).

Rudisill et al. (2023) and Muniz Medeiros et al. (2021) reported effects of eccentric resistance training on measures of both concentric and eccentric strength. For concentric strength, the authors reported trivial – small effects (g = -0.09 – 0.45) from the studies of Brughelli et al. (2010); Ribeiro-Alaves et al. (2017) Delvaux et al. (2020) and Mendiguchia et al. (2015), but moderate – large (g = 0.93 – 1.34) positive effects from Anastasi and Hamzeh (2011); Askling et al. (2003) and Ryan et al. (1991).The overall standardised effect for concentric was *g* = 0.53 (95% CI -0.23 - 1.30) For measures of eccentric strength, small (*g* = 0.44 – 0.47) beneficial effects were reported for the studies of Iga et al. (2012) and Ribeiro-Alaves et al. (2017) and moderate - large (*g* = 0.80 – 1.28) beneficial effects from the studies of Askling et al. (2003); Salci et al. (2013); Suarez-Arrones et al. (2019) and Mendiguchia et al. (2015). Interestingly, only Askling et al. (2003) found large positive effects in both concentric and eccentric knee flexor strength, which resulted from a 10-week prone lying flywheel training intervention in soccer players, consisting of 16 sessions of 4x8 repetitions. Mendiguchia et al. (2015) reported small (*g* = 0.39) beneficial effects for concentric strength but moderate (*g* = 0.80) beneficial effects in eccentric strength. The overall standardised effect for eccentric strength was *g* = 0.66 (95% CI 0.121 – 1.44). Of the studies included for meta-analysis, the majority (Brughelli et al. 2010; Ribeiro-Alaves et al. 2017; Delvaux et al. 2020; Mendiguchia et al. 2015 and Askling et al. 2003) reported that there were no significant differences in strength or anthropometric characteristics between control and intervention groups at baseline. Only the studies of Suarez-Arrones et al. (2019) and Ryan et al. (1999) did not provide clear indication of whether any baseline differences existed between groups. Further, most studies included reported compliance rates of ≥ 70%, with only Suarez-Arrones et al. (2019) and Ryan et al. (1999) failing to report compliance with the training intervention.

The differences in positive adaptations between the studies of Askling et al. (2003) and Mendiguchia et al. (2015) may serve to highlight the importance of training intensity on subsequent adaptations. Participants in Askling et al. (2003) were instructed to complete all repetitions with maximal intensity and given the nature of inertial training, a high concentric effort must be matched by the eccentric effort to create negative acceleration, meaning that if all efforts were maximal then high eccentric intensities would have been achieved in all training sessions. In the study of Mendiguchia et al. (2015), the training intervention was shorter in duration (7 weeks *versus* 10 weeks), but also participants were only exposed to supramaximal eccentric loads (NHE) in every other week of the programme, with the only other resistance training elements of the programme being performed at very low absolute and relative loads (e.g., 15 kg deadlifts and hip thrusts at 70% of body mass). Similarly, other studies that have utilised supramaximal training intensities through the NHE (Anastasi and Hamzeh, 2011) or maximal isokinetic training intensities (Ryan et al. 1991) were found to elicit moderate positive improvements in concentric knee flexor strength. Whereas studies such as Brughelli et al. (2015) utilised exercises that were unlikely to expose participants to a near maximal concentric or eccentric knee flexor or hip extensor effort such as dropping from a box, lunges while pushing against a wall, pulling back on a partner as they run or the reverse Nordic curl.

Contrastingly, Delvaux et al. (2020) utilised supramaximal eccentric training through the NHE, alongside other exercises such as supine knee slides, unloaded single leg RDLs and the Askling glider over a 6-week period. Although the programme did include a supramaximal eccentric stimulus, the progressive nature of the NHE repetitions required participants to complete three sets of ten NHEs three times per week from weeks 4-6 of the programme along with three sets of ten repetitions of the other 3 exercises in each training session. There is therefore a potential that due to the 120 total session repetitions, the accumulation of within-session fatigue may have led to a decrease in repetition intensity which may explain the lower magnitude of adaptation compared with other studies that included maximal or supramaximal intensities (Anastasi and Hamzeh, 2011; Askling et al., 2003; Meniguchia et al., 2015 and Ryan et al., 1991). Ribeiro-Alaves et al. (2017) and Iga et al. (2012) also utilised progressive NHE programmes that built up to three sets of ten NHEs twice per week and three sets of eight repetitions three times per week, respectively but the total intervention durations were only 4-weeks which may indicate that this period of time is not sufficient to elicit more than small positive adaptations in eccentric or concentric knee flexor strength.

Bourne et al. (2017) compared 10-weeks of NHE or Roman chair hip extension training to a control. Standardised magnitudes of differences in peak eccentric knee flexor (NordBord) strength showed large effects (g = 1.23) favouring the Roman chair hip extensor group, with both the Roman chair hip extensor group and NHE group eliciting very large positive beneficial effects over the control group (g = 11.31 and 9.79, respectively). Differences between the two intervention groups, although large in magnitude, did not meet the threshold for statistical significance ($p \leq 0.05$), perhaps due to the relatively small sample size in each group (n = 10). Given that both intervention groups experienced significant and very large improvements compared with the control, the authors speculated that this may indicate that adaptations in knee flexor strength are not highly specific to the chosen exercise. While the findings of Bourne et al. (2017) may indicate that adaptations may not be highly exercise specific, it should be noted that adaptation is still likely to be dictated by intensity given the previously discussed studies of Mendiguchia et al. (2015) and Brughelli et al. (2015) that reported only trivial-small improvements from arguably low intensity training programmes. Furthermore, while both the NHE and Roman chair hip extension groups in Bourne et al. (2017) experienced significant and very large improvements in strength over the control group, these improvements were larger in the Roman chair hip extension group. This potential for larger magnitude of improvements may be due to longer muscle-tendon unit lengths associated with the Roman chair hip extension compared to the NHE. Recent systematic reviews and meta-analyses, Wolf et al. (2023) and Kassiano et al. (2023) reported that resistance training at longer muscle lengths may lead to superior adaptations in muscle hypertrophy compared to training at shorter muscle lengths, however further research is needed to examine the effects of training at longer muscle lengths for adaptations in strength and specifically in the hamstring muscle group.

There exists a broad range of training volumes and intervention durations in the reported literature. Currently, only Cuthbert et al. (2020) have directly meta-analysed the effect of training volume and intervention duration on adaptations in hamstring muscle strength. Such analyses into training volumes are key to allow practitioners to best understand the potential minimum effective dosages for positive training adaptation. Over the last two decades, there has been a surge in the number of scientific publications specifically focused on the NHE as a training intervention for the mitigation of HSI risk and individual risk factors. In some of the earliest seminal work on the NHE as a training intervention Mjølsnes et al. (2004) recommended a progressive NHE training programme which built up towards weekly NHE volumes of 90 repetitions per week. Mjølsnes et al. (2004) reported very large (g = 2.12; 95% CI 1.37 – 2.87) beneficial effects of this high-volume NHE programme, although later studies of Selci et al. (2013) and Siddle et al. (2019) reported moderate (Selci et al., 2013, g = 0.74; 95% CI -0.16 – 1.64) to large (Siddle et al. 2019, g = 1.32; 95% CI – 0.51 – 3.15) positive beneficial effects when the protocol was replicated with recreational athletes.

However, a later survey conducted by Bahr et al. (2015) revealed that the protocol of Mjølsnes et al. (2004) was only being adopted in 16 (10.7%) of 150 club seasons surveyed at the elite (UEFA Champions League) or Norwegian Tippeligaen (now Eliteserien) level. The finding that elite-level soccer clubs were not adopting such a protocol is unsurprising given the high volumes and high-time commitment needed for a single exercise intervention and the likely association with delayed onset muscle soreness associated with high-volume NHE training (Behan et al., 2023). Further to this, even traditional resistance training recommendations by the likes of the National Strength and Conditioning Association (NSCA), are in the region of ≥85% 1 repetition-maximum (RM) for ≤ 6 repetitions. Therefore, given that the NHE is meant to be a supramaximal (i.e., ≥ 1 RM), it raises questions as to the rationale behind such high volumes.

Interestingly. Cuthbert et al. (2020) also presented their findings in relation to magnitudes of effect for training interventions ranked from highest to lowest total training volume as well as shortest to longest training intervention. It was concluded that while there was no trend with respect to training volume with both high and low volume NHE training programmes demonstrating potential to elicit very large magnitudes of effect, the authors did recommend a threshold of 6 weeks for a minimum intervention duration to elicit positive adaptation in strength. Of the eight studies included in the 4-6 (Freeman et al., 2019; Alt et al., 2018; Clark et al., 2005; Iga et al., 2012; Ribeiro-Alvares et al., 2017; Tansel et al., 2008; Dalahunt et al., 2016; and Presland et al., 2018) week intervention duration group, those that conducted interventions of 4-weeks in duration reported trivial – small effects. Moderate – very large effects were reported in the medium duration (8-10 week) group (Mjølsnes et al., 2004; Ishøi et al., 2018; Seymore et al., 2011 and Anastasi and Hamzeh, 2011) with one 6-week intervention group reporting large – very large positive effects (Presland et al., 2018). The study by Amundsen et al. (2022) which was published after the meta-analysis of Cuthbert et al. (2020) compared 8-weeks of either high volume (Mjølsnes et al., 2004 protocol, 21 sessions, 538 total repetitions) compared with low volume (10 sessions, 144 total repetitions), Similar to the findings of Cuthbert et al. (2020) Amundsen et al. (2022) found no additional benefits of higher volume NHE with no statistically significant differences between group (p = 0.52). However, it should be noted that although both groups experienced significant strength increases, these were only small in magnitude (high volume g = 0.22; low volume g = 0.38). Furthermore, the actual NordBord values reported in both groups by Amundsen et al. (2022) were generally low (303 ± 37 N and 316 ± 46 N at the end of the study for the high and low volume groups, respectively). Although the participants in the study were soccer players from the Norwegian second division, these NordBord scores do indicate that the participants were weak and therefore there is a potential that participants were not strong enough to maintain the repetitions to allow a sufficient eccentric overload to occur which could in-turn have led to the magnitudes of adaptation being small.

2.5.2 Effects of Training on Athletic Performance

In addition to utilising resistance training with an eccentric bias for the development of muscle strength to potentially mitigate risk of HSI, research also exists in relation to potential beneficial effects on athletic performance such as sprint running, change in direction and jump performance. In a systematic review and meta-analysis Bautista et al. (2021) investigated the standardised effects of NHE training on sprint running performance between distances of 5 – 20 m in team sport athletes. The random effects model revealed a moderate positive beneficial effect of NHE training on performance across the pooled investigated distances (g = 0.61; SMD -0.04 s; 95% CI -0.09 - -0.01). Standardised magnitudes of effect for studies that reported changes in 5 m performance ranged from trivial-moderate (g = 0.08 – 0.94). For 10 m performance, the standardised positive beneficial effects ranged between trivial – moderate (g = 0.05 – 0.95) and between small – moderate for 20 m performance (g = 0.29 – 1.04). Only Mendiguchia et al. (2020) reported any negative (small) effects of NHE on sprint performance in the 5 m and 20 m distances (g = 0.40 and 0.34, respectively). From the meta-analysis results of Bautista et al. (2021), it was concluded that there is relatively weak evidence with some risk of bias to support meaningful beneficial effects of NHE training on sprint performance. The standardised mean difference across the pooled distances of -0.04 is larger than the smallest worthwhile effects of 0.02 s for 20 m sprint performance as reported by Haugen et al. (2014) and the smallest worthwhile changes in 40 m sprint performance reported by Haugen and Bucheit (2016) and Shahab et al. (2020) which may indicate some meaningful benefits. As with the use of NHE training for adaptations in strength, there is a broad range in the training volumes, frequencies and intervention durations in the studies included in the meta-analysis of Bautista et al. (2020) which may have affected the results. Additionally, a lack of ecological validity could be highlighted here given that it is unlikely that applied practitioners would utilise only the NHE as a means of developing sprint performance. Furthermore, given that the participants used in these studies were team sport athletes, it is not clear to what extent they were engaged in HSR or sprint running based training in addition to the NHE intervention which adds to the caution which should be applied when interpreting these findings.

Since the publication of the meta-analysis by Bautista et al. (2021), Ripley et al. (2023) investigated the addition of either the NHE or sprint running training to a resistance training programme on hamstring strength, jump performance and sprint running performance. Both training intervention groups experienced significant-moderate improvements in 0 – 10 m ($p \leq 0.05$; $g = 0.69 – 0.76$) and 0 – 20 m ($p \leq 0.05$; $g = 0.67 – 0.68$) sprint performance, with significant-small and moderate improvements in 10 – 20 m sprint performance in the NHE and sprint groups, respectively ($p \leq 0.05$; g = 0.47; 0.71). Sancese et al. (2023) investigated the effects of a 4-week NHE (10 weekly repetitions, progressing to 18) *versus* sprint training (5x20 m progressing to 6x40 m), but found non-significant and small ($p \geq 0.05$; g 0.47; 95% CI -1.99 – 1.05) effects on 30 m sprint times. Amundsen et al. (2022) reported non-significant and trivial differences ($p \geq 0.05$; $g = -0.18 – 0.09$) in sprint performance in female soccer players from 8-weeks of NHE training using a shortened version of the Mjølsnes et al. (2004) et al. high-volume (538 total NHE repetitions *versus* low volume (144 total NHE repetitions).

The findings of Ripley et al. (2023) are in contrast to those of Sancese et al. (2023), Amundsen et al. (2022) and Mendiguchia et al. (2020) and may highlight that to induce meaningful changes in sprint performance, resistance training programmes should include more than just the NHE (e.g., Ripley et al. [2023] and Mendiguchia et al., [2020]), however resistance training programmes included the addition of either the NHE or sprint based training, which appear to yield comparable adaptations in sprint performance. However, while it is important to include more exercises than just the NHE, likely due to the multi-joint nature of sprint running, exercise intensity is likely a key determinant of adaptation, as seems to be the base from the previous section on the effects of hamstring training for muscle strength. This is highlighted by the contrasts between the findings of Mendiguchia et al. (2020) and Ripley et al. (2023). Both studies utilised concurrent sprint and resistance training, but the overall relative training loads used by Ripley et al. (2023) were notably higher. So, while both studies reported positive adaptations in knee flexor strength, Ripley et al. (2023) reported significant-moderate positive effects on sprint performance, whereas Mendiguchia et al. (2020) reported small negative changes in sprint performance.

Alt et al. (2021) also reported significant, but small ($p \leq 0.05$; $g = 0.20 – 0.51$) adaptations sprint performance in national-level sprinters from a 4-week NHE programme which consisted of both assisted and unassisted NHEs. However, a key difference between the study of Alt et al. (2021) compared with Sancese et al. (2023) is that participants in the study of Alt et al. (2023) maintained an angular velocity of 15°·s^{-1} through a 90-100° range of motion, which may have aided adaptations in ensuring a consistent time under tension and repetition intensity across all training repetitions. The importance of training intensity may also be further highlighted by the study of Alonso-Fernandez et al. (2018) that found no significant ($p \geq 0.05$; $g = 0.16 – 0.48$) changes in sprint performance from 8-weeks of training using the Askling L-protocol (Askling et al., 2013; Askling et al., 2014), (comprising of unloaded supine knee extensions, unloaded single leg RDLs and a standing, weightbearing hip flexion in which the foot slides forward on a low friction surface) compared to a control group. Furthermore, Kamandulis et al. (2020) investigated traditional leg curls, concentric only leg curls and high velocity prone lying banded tantrums on sprint performance. The authors reported no significant differences in sprint performance in the leg curl groups ($p \geq 0.05$; $g = -0.32 – 0.00$), but significant and moderate improvements in 10 – 30 m performance ($p \leq 0.05$; $g =$ -0.89 – 1.26; 95% CI -0.89 – 1.26), and 30 m performance from a flying start ($p \leq 0.05$; $g = 0.77$; 95% CI -0.35 – 1.88) in the tantrum group. Kamandulis et al. (2020) stated that these results indicate that high velocity banded exercise is superior to traditional or concentric-only resistance training for eliciting positive adaptations in sprint performance, however given that vague details of the training programme, these data should be interpreted with caution. For instance, the leg curls were stated as being progressed from 4-6 sets and from three to one repetition at 95-100% intensity, but as no repetition maximum testing was stated, it is not clear if this was based on intensity meaning intent to complete the movement with maximal velocity or if these values were truly representative of a 95-100% of repetition maximum. Additionally, the tantrum exercises were maximal effort for 4 s. Although the sets were matched, it is likely that the total volume of repetitions was much higher in the tantrum group, meaning that some of the adaptations may be attributable to differences in volume rather than load between the two groups. There is also scope to critique the underpinning principles of tantrum-type exercises in comparison to other approaches to training such as the NHE or Roman chair hip extension. Given the very high movement velocity and extremely short contact times with the resistance band, the time under tension is also extremely low as is the range of motion that is utilised while the limb is in contact with the band. As a result, while tantrum-type exercises may be associated with high-levels of muscle excitation (Tsaklis et al., 2015) due to the high contraction velocity, it seems unlikely that such exercises would lead to meaningful improvements in muscle strength or athletic performance.

Amundsen et al. (2022) and Ripley et al. (2023) have quantified the effects of hamstring specific training on measures of CMJ performance, with varying degrees of success. For instance, Amundsen et al. (2022) reported non-significant and trivial differences in CMJ height between high and low volume NHE intervention groups (p = 0.20; g = 0.18). While the authors did report significant decreases in CMJ height in the high-volume training group, the trivial effect size likely indicated that this decrease was not meaningful (p = 0.08; g = 0.13). Similarly, Ripley et al. (2023) reported non-significant between group differences in CMJ take-off velocity and jump momentum between the NHE, sprint running and control groups (p = 0.834 and 0.518, respectively). However, individual within group comparisons revealed significant improvements in take-off velocity in all three groups which were small in magnitude for the NHE and control groups ($p < 0.001$; $g = 0.48$), but moderate in the sprint running group ($p < 0.001$; $g = 0.64$). Changes in jump momentum were non-significant in the NHE group ($p = 0.154$; $g = 0.29$), but significant-small improvements were reported in the sprint running and control groups ($p = 0.045$; $g = 0.57$ and $p = 0.013$; $g = 0.45$, respectively). While both Amundsen et al. (2022) and Ripley et al. (2023) reported non-significant between-group differences in jump performance, positive and meaningful effects were only reported by Ripley et al. (2023). The reason for the enhanced beneficial effects reported by Ripley et al. (2023) is likely due to the multi-modal training programme used which incorporated the addition of either sprint running or the NHE to a resistance programme that included the power clean, back squat, reverse lunge, RDL and mid-thigh pull, rather than only the NHE used by Amundsen et al. (2022). Ripley et al. (2023) postulated that given the addition of either the NHE or sprint running had less of an effect on jumping that the control programme, the positive changes in jump performance were likely attributable to the traditional resistance training programme. Another potential reason for the different findings from Amundsen et al. (2022) may be down to measurement error. The authors chose to only report CMJ height even though all CMJs were performed on a force plate. While Amundsen et al. (2022) used a different force plate system than Ripley et al. (2023), the standard error of measurement and smallest detectable difference for CMJ height (%SEM 36.82; %SDD 102.07) has been reported as higher than measurements such as take-off (%SEM 1.56; %MDD 4.34) velocity, indicating that jump height alone may not be a sensitive enough measurement to detect true changes in jump performance.

However, the standard error of measurement or minimum detectable difference was not reported by Amundsen et al. (2022) so this is purely speculative.

2.6 Objectives of the Research

From the literature review, a number of gaps were identified that require investigation in the current thesis. These areas include, methods used to make informed decisions on exercise selection, methods used to assess and monitor knee flexor strength, the applied practices of strength and conditioning practitioners in relation to multi-modal exercise interventions for the mitigation of hamstring strain injury risk and development of athletic performance and the adaptations to ecologically valid training interventions beyond single exercise interventions such as the NHE. These gaps in the literature have formed a number of research objectives, outlined below, which will be addressed within the thesis. Ultimately, the research objectives will aim to address the broader overarching aim of methods which could be used in applied practice for the mitigation of HSI risks and the development of athletic performance.

1. Practices and perceptions in hamstring training for injury prevention and enhancement of athletic performance mixed-methods analysis.

Claims have been made by the likes of Bahr et al. (2015) that evidence-based HSI ‘injury prevention’ recommendations are not adopted in elite-level soccer. However, the specific recommendations that the authors were referring to were based on extremely high volumes of over 90 NHE repetitions per week, and repetition schemes that exceed the recommendations from the likes of the NSCA for the development of maximum strength. Therefore, it is unsurprising that such recommendations were not being followed by applied practitioners. Furthermore, it seems unlikely that applied practitioners would use only one single exercise for the development of hamstring strength or mitigation of other modifiable risk factors for HIS. While researchers such as Weldon et al. (2021a, 2021b, 2021c, 2022) have more recently investigated general S&C practices in sports such as soccer, cricket and volleyball, currently there is very little understanding of the applied practices specific to the mitigation of HSI risk, monitoring of HSI risk or training practices focused on the development of athletic performance such as maximal velocity running.

2. The within session reliability of methods to normalise electromyography amplitudes in the gluteal and hamstring muscles.

Numerous researchers have made exercise selection recommendations based on EMG amplitudes alone (Zebis et al., 2013; Tsaklis et al., 2015; van den Tillaar et al., 2017). However, there is a lack of consensus regarding reported EMG amplitudes across commonly investigated exercises such as the NHE and variations of the hip hinge. While this lack of consensus can be partly explained by variations in exercise technique and load selection, there is also a lack of consensus for or justification of the method of amplitude normalisation that has been used to compare between exercises or studies. Given that amplitude normalisation directly affects the results of such exercise-selection studies, there is a need for investigators to select amplitude normalisation methods that are associated with acceptable levels of reliability and are truly representative of maximal effort contraction.

3. A kinetic and electromyographic comparison of the Romanian deadlift and good morning exercises.

Several authors have investigated exercise selection principles beyond just EMG alone. For instance, Sarabon et al. (2019) have conducted kinetic analyses of the NHE and variants, including different shank slope angles. Bourne et al. (2015) have investigated EMG and T2 relaxation times following various hamstring exercises and Lee et al. (2018) investigated kinetic differences between the conventional and Romanian deadlifts. However, it was evident from the qualitative analyses in the current thesis that practitioners considered hip hinge-based exercises as cornerstones of their regular training practices with their athletes. As a result, there is a need to better establish the kinematic, kinetic and muscle excitation characteristics of commonly used exercises such as the Romanian deadlift and good morning to better inform practitioners on their exercise selection and potential adaptations to training.

4. The reliability and force-time characteristics of the Nordic hamstring exercise.

The NHE is arguably the most commonly investigated exercise for the development of hamstring-specific strength and has also been broadly investigated as a means of assessing knee flexor strength since its introduction to the scientific literature in 2013 (Opar, et al., 2013). However, the majority of researchers that have used the NordBord to quantify knee flexor strength have focused only on peak force, which restricts analyses to only one single time point across an entire force-time series. Additionally, the original reliability of the NordBord reported by Opar et al. (2013) was based on a prototype model which had a much larger sample frequency than the commercially available device. Consequently, there is a need to establish analyses beyond peak force alone as well as establish reliability of the commercially available NordBord.

5. Integration of a knee flexor bias or hip hinge bias resistance training programme with concurrent high-speed running in academy soccer players

Several authors have investigated adaptations to single exercise interventions such as the NHE (Cadu et al., 2022; Mjølsnes et al., 2004; Presland et al., 2018; Anatasi and Hamzeh, 2011; Iga et al., 2012; Ribeiro-Alvares et al., 2017; Seymore et al., 2017; Tansel et al., 2008 and Ishoi et al., 2018) and while such studies provide valuable insight into the potential benefits of such training, they are lacking in ecological validity. While authors such as Freeman et al. (2019), Mendiguchia et al. (2020) and Sancese et al. (2023) investigated adaptations in sprint trainingt *versus* NHE training and Marchiori et al. (2022) compared adaptations from NHE *versus* RDL training, only Ripley et al. (2023) has reported adaptations from an ecologically valid resistance training programme with the addition of either the NHE or sprint training. However, comparisons between concurrent sprint and resistance training with either a NHE or hip hinge bias are currently lacking in the literature.

Chapter 3 Practices and Perceptions in Hamstring Training for Injury Prevention and Enhancement of Athletic Performance: A Survey-Based Mixed-Methods Analysis.

3.1 – Background

Hamstring strain injuries are a common occurrence across multiple sports, however there is no clear consensus on the approach to training for the reduction of risk factors associated with injury, or with the aim of achieving an enhanced level of athletic performance. Previous research from the likes of Weldon et al. (2020; 2021a) has provided qualitative and quantitative data on general strength and conditioning practices in areas such as cricket and volleyball, which has helped to highlight some of the limitations and challenges of practices in these such sports, particularly concerning a perceived lack of time with athletes; facilities and access to equipment. Furthermore, Freeman et al. (2021) surveyed the beliefs and practices of physical performance coaches working in the elite level of Australian rules football. The research from Freeman et al. (2021) highlighted a potential disparity in opinion with regard to the use of global positioning systems (GPS) to monitor sprinting in the AFL as well as a disparity between the perceptions around thresholds used to define absolute and relative (% of maximum) HSR and sprint velocities. While epidemiological data exists in relation to HSI across a range of sports, as well as numerous observational studies in relation to training and match-play demands (such as volume, frequency and distances covered through HSR), little is known about applied training practices of practitioners working in these sports. Given that training practices such as exposure to HSR, resistance training methods and ongoing athlete assessment methods are likely to play a key role in the frequency and severity of HSIs, (Green et al., 2020) further development of knowledge of how common practices may influence injury epidemiology is crucial in the ongoing pursuit of a reduction in HSIs.

Furthermore, little is currently known about how education influences applied training practices. For instance, the philosophical or evidence-informed approach to training practitioners may adopt based on their profession (such as physiotherapist, strength and conditioning coach, sports rehabilitator, sports scientist), level of experience, level of academic qualification or accreditation. Further still, there is a range of formal (e.g., undergraduate, postgraduate) degree programmes, formal accreditations, vocational qualifications and informal study routes such as self-directed study, networking and continued professional development opportunities such as attendance to conferences, which may all have an effect on the applied practices and training philosophes of those working in with athletes. Additionally, little is known about differences in training approaches across geographical regions or experiences working with particular sporting populations. For instance, it was observed that the number of HSIs may have decreased in Australian football from an average of 24.3 matches missed per club per season due to HSI in 2007 to 19.7 in 2016. Although in terms of new injuries per club per season, this decrease was 6.7 new injuries in 2007 compared with 5.2 in 2016 (AFL Doctors Association & AFL Physiotherapists Association, 2016). In elite European soccer, it was reported by Ekstrand et al. (2016) that HSI incidence increased by 4% annually between 2001 - 2014, which questions whether training practices may differ between Europe and Australia and even differences in practice within Europe may differ given the disparity between HSI incidence between the likes of the English Premier League and German Bundesliga. Whereas in the American collegiate system, it is common for scholarship athletes to engage in multi-sports as well as have a greater resistance training age, compared with academy soccer players in the United Kingdom, which then begs the question of how does training practice and philosophy differ between practitioners working across sports.

Over the past 15 years, there has been a surge in the volume of research published in peer-review journals relating to hamstring strain injury and potential intervention methods to reduce occurrence rates. However, despite this surge in research, there is little evidence for a clear reduction in HSI incidence and even a potential increase in incidence (Ekstrand et al., 2016; Ekstrand et al., 2022). Furthermore, some authors have suggested that HSI risk mitigation protocols proposed in the literature are not applied in practice (Bahr et al., 2015). Therefore, there is a clear need to develop an understanding of real-world practices and the underpinning rationale of practitioners to gain an understanding of how practices differ across sports, practitioners and regions of the world.

Bahr et al. (2015) conducted a survey of practitioners at UEFA Champions League and Norwegian Tippeligaen (now known as the Eliteserien) and concluded that evidence-based guidelines for the implementation of the NHE are not adopted in elite level soccer. However, the authors were referring to a specific 10-week NHE protocol originally proposed by Mjølsnes et al. (2004) with progressive volume increases which consisted of extremely high volumes of up to 90 repetitions of the NHE per week. The lack of application of such a protocol seems understandable given the substantial time commitment required, particularly at the elite-level with squad sizes of ≥25 players. While the original protocol by Mjølsnes et al. (2004) has been shown reduce HSI risk factors through increases in eccentric knee flexor strength and BFLH FL and decrease PA, questions can be raised as to whether similar adaptations could be achieved with lower volumes of training, especially when considering that the volumes proposed by Mjølsnes et al. (2004), are much higher than the repetition ranges recommended by the likes of the NSCA (Haff and Triplett, 2016) for the development of maximal muscle strength. More recently Cuthbert et al. (2019) conducted a systematic review and meta-analysis to investigate the effects of NHE volume on adaptations in knee flexor strength and FL and found that lower volumes (as low as around 8 repetitions per week), of ≥6 weeks do not have a negative effect of subsequent adaptation in comparison to higher volume interventions, or longer protocols such as the 10 weeks in the original Mjølsnes et al. (2004) study. This seems promising as lower volumes may be a lot more realistic and appealing to practitioners and may mitigate some of the negative aspects of higher volume training such as delayed onset of muscle soreness (DOMS). However, while DOMS may be perceived as a barrier to the implementation of programmes such as that proposed by Mjølsnes et al. (2004), it must be noted here that the authors did record participant's perceived muscle soreness on a 0-10 scale following the first 7 training sessions of the programme and found that none of the 21 participants reported a soreness score greater than 3/10. Additionally, Mjølsnes et al. (2004) also reported a 96% compliance rate with the programme, however the participants were from a sample of students competing in the 2nd to 4th division of Norwegian University football and therefore the same compliance rate may not be realistic in an elite setting with higher volumes of technical and tactical training as well as periods of multiple competitive fixtures and associated travel within the training week.

It has been shown by the likes of Ripley et al. (2021) that compliance to training interventions has a positive effect on the incidence of HSI, with a compliance of ≥50.1% and a consistent approach of ≤3 weeks/per session. Additionally, Ripley et al. (2021) observed that eccentrically focused interventions were superior to interventions without a specific eccentric focus. Therefore, if the application of low-volume training can be effective in mitigating HSI risk factors, and has the potential to increase compliance with training, practitioners may be able to achieve positive results in reducing the incidence of HSI with a relatively low training volume and frequency.

While surveys by the likes of Bahr et al. (2015) provided valuable insight into applied practices and developed an understanding that some of the early evidence-based protocols for the reduction of HSI incidence, and the likes of Weldon et al. (2020; 2021a) have more recently developed a broader understanding of applied S&C practices in several sports, there is still a lack of understanding of applied practice and whether recent developments in the scientific literature are translating into applied practice. Additionally, the existing HSI literature is limited by most training intervention studies somewhat lacking in ecological validity by focusing on the effects of one single exercise (such as the NHE) in isolation, rather than as part of a holistic training programme. Therefore, developing an understanding of how the exercise is programmed as part of wider training can help to develop an understanding of practice and can influence the development of future training intervention studies.

3.1.1 Aims and Hypotheses

The aim of this study was to survey practitioners to develop a more detailed overview of the applied practices in sport. The survey was designed to cover a range of aspects in relation to the practitioner profile as well as the applied practices in relation to resistance training, use of high-speed running as a training intervention, athlete monitoring and practitioner perceptions and philosophies which underpin their practices.

It was hypothesised that practitioners would use lower volumes of the NHE than advocated by the likes of Mjølsnes et al. (2004) but that the NHE would be used in conjunction with other hamstring resistance training methods. It was hypothesised that high-speed running would be programmed by practitioners at likely higher-volumes during the off-season than in-season. It was also hypothesised that practitioners would refer to limiting factors such as DOMS as barriers to implementation of resistance training in their practice.

3.2 – Methodology

3.2.1 Study Design

The study used an anonymous online survey to investigate the practices and perceptions of hamstring training in relation to injury prevention and enhanced athletic performance across sport and exercise practitioners. The survey was developed using the open-access survey application 'Google Forms'. The survey was presented in English language only and was comprised of six subsections: (a) written informed consent; (b) professional profile; (c) off-season training practices; (d) in-season training practices; (e) approaches to testing and training; and (f) training and testing philosophy. While the full details of the survey can be found in APPENDIX 1.0, the survey covered (not including informed consent questions) 27 fixed-response questions which included Likert/multiple choice and 'all that apply' style questions and 21 open-ended questions, intended to allow participants to provide a qualitative rationale or underpinning philosophy to their responses. Prior the survey being made accessible to practitioners, pilot testing was carried out using six participants (four strength and conditioning coaches and two sports therapists), known to the candidate, which allowed for discussion around the wording of questions, user interface/structure and general feedback. The pilot testing resulted in some minor changes to wording of some questions and an increased use of fixed response questions. The increase in the use of fixed response questions was due to a number of pilot responses including information that was interpretable in a fixed style response, but subtle differences in wording and grammatical presentation, such as use of capital letters and Oxford commas, made for a more laborious coding of responses.

The first subsection of the survey covered informed consent and provided participants will a link to access the full participant information sheet (APPENDIX 2.0). The informed consent section consisted of seven compulsory questions which prompted participant to confirm that they had read the participant information sheet, fully understood the rationale and methods of the study and understood the process for voluntary withdrawal if they so wished. Participants were provided with contact details of the candidate and supervisory team to ask any questions prior to taking part. As all responses were anonymous, even if a participant had made contact to ask questions of the candidate, their actual survey responses would remain anonymous. As all informed consent questions were compulsory, if the participant failed to provide an answer or were not able to agree to any aspect of informed consent, they were provided with an error message to either inform them that they had not provided informed content (in case this was done in error), or to thank them for considering participation in the survey even if they were unable to consent to taking part. Participants were not able to proceed to the responses in the remaining five subsections if they did not provide informed consent.

Chapter 3.2.2 – Participants

A total of 47 practitioners responded to the survey. All descriptive data regarding the profile of the responders is presented in Table 3-1. As some aspects of the professional profile allowed for multiple responses, such as sports worked in, qualifications held, accreditations held and typical job role and responsibilities, those sections have been expanded to include all responses, hence exceeding 47 responses.

Table 3-1 A-I Shows descriptive characteristics of the survey responses from the survey based on professional profile. NSCA = National Strength and Conditioning Association; UKSCA = United Kingdom Strength and Conditioning Association; SST = Society of Sports Therapists; BASES = British Association of Sport and Exercise Scientists; CSP = Chartered Society of Physiotherapists; NATA = National Athletic Trainer's Association; APA = Australian Physiotherapy Association; ASCA = Australian Strength and Conditioning Association; ESSA = Exercise and Sport Science Australia; STA = Sports Therapy Association; CATA = Canadian Athletic Trainer's Association; BASRaT = British Association of Sports Rehabilitators and Trainers; STO = Sports Therapy Organisation; A.I.F.I = Associazione Italiana di Fisioterapia (Italian Physiotherapy Association); Rugby NS = specific Rugby format not specified.

A - Sex of Participants

	Profession						
Sex	**Strength and Conditioning Coach**	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Athletic Therapist**	**Sports Rehabilitator**	**Total**
Male	15	11	3	8	0	2	39
Female	2	3	-	2	1	-	8

B – Participant Age Range

	Profession						
Age Range (years)	**Strength and Conditioning Coach**	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Athletic Therapist**	**Sports Rehabilitator**	**Total**
18-24	3	7	-	-	-	-	10
25-34	10	5	2	6	-	1	23
35-44	3	2	1	4	1	1	12
45-54	1	-	-	-	-	-	1

C – Years Spend in Current Profession

Years in Current Profession	Profession						
	Strength and Conditioning Coach	Sports Therapist	Sports Scientist	Physiotherapist	Athletic Therapist	Sports Rehabilitator	Total
<1 year	-	3	-	-	-	-	3
2-3 years	3	5	-	-	-	-	8
4-5 years	3	1	-	2	-	-	6
3-5 years	1	-	1	-	-	-	2
6-10 years	5	2	2	3	-	1	13
11-15 years	3	2	-	2	-	1	8
>15 years	2	1	-	3	1	-	7

D – Country Currently Practicing In

Country	Profession						
	Strength and Conditioning Coach	Sports Therapist	Sports Scientist	Physiotherapist	Athletic Therapist	Sports Rehabilitator	Total
UK	12	11	2	7	-	1	33
Australia	1	-	-	2	-	-	3
Gibraltar	-	2	-	-	-	-	2
USA	2	-	-	-	-	-	2
Sweden	-	1	-	-	-	-	1
Canada	1	-	-	-	1	-	2
South Africa	1	-	-	-	-	-	1
Singapore	-	-	1	-	-	-	1
Italy	-	-	-	1	-	-	1
Greece	-	-	-	-	-	1	1

E – Athlete Groups Currently Working With

Athlete Groups	Profession						
	Strength and Conditioning Coach	Sports Therapis t	Sports Scientist	Physiotherapist	Athletic Therapist	Sports Rehabilitator	Total
Soccer	12	13	2	5	-	1	33
Track and Field	6	-	-	3	-	-	9
Combat Sports	2	1	1	-	-	-	4
Rugby (NS)	4	1	-	1	-	-	6
Rugby Union	2	1	-	-	-	1	4
Rugby League	1	-	-	1	-	-	2
Rugby Sevens	1	-	-	-	-	-	1
Lacrosse	1	-	-	-	1	-	2
Hockey	3	-	-	-	1	-	4
Netball	1	-	-	1	-	-	2
Tennis	2	-	-	-	-	-	2
Volleyball	3	-	-	-	-	-	3
Basketball	2	-	-	-	-	-	2
Australian Football	1	-	-	1	-	-	2
Baseball	2	-	-	-	-	-	2
Football	1	-	-	-	-	-	1
Softball	1	-	-	-	-	-	1
Cricket	1	-	-	-	-	-	1
Ultramarathon	-	1	-	-	-	-	1
Triathlon	-	1	-	-	-	-	1
Long Jump	-	1	-	-	-	-	1
Cycling	-	1	1	-	-	-	2

F – Level of Athlete Currently Working With

Athlete Level	Profession						
	Strength and Conditioning Coach	Sports Therapist	Sports Scientist	Physiotherapist	Athletic Therapist	Sports Rehabilitator	Total
Professional	9	10	3	9	1	2	34
University / College	8	2	-	4	-	1	15
Semi-pro	1	4	-	-	-	-	5
Youth	6	6	1	4	-	-	17
High School	7	2	-	3	1	-	13

G – Highest Academic Qualification Held

Highest Qualification	Profession						
	Strength and Conditioning Coach	Sports Therapist	Sports Scientist	Physiotherapist	Athletic Therapist	Sports Rehabilitator	Total
Bachelor's degree	2	9	-	6	-	-	17
Master's degree	11	4	2	4	1	2	24
PhD / Doctorate	4	1	1	-	-	-	6

H – Number of Years Since Achieving Highest Level of Qualification

Number of Years	Profession						
	Strength and Conditioning Coach	Sports Therapist	Sports Scientist	Physiotherapist	Athletic Therapist	Sports Rehabilitator	Total
<1 year	3	5	1	-	1	-	10
2-3 years	6	5	1	2	-	-	14
4-5 years	2	1	1	4	-	-	8
6-10 years	5	3	-	1	-	2	11
11-15 years	-	-	-	2	-	-	2
>15 years	1	-	-	1	-	-	2

I – Professional Memberships and Accreditations Held

	Profession						
Membership / Accreditation	Strength and Conditioning Coach	Sports Therapist	Sports Scientist	Physiotherapist	Athletic Therapist	Sports Rehabilitator	Total
SST	-	13	-	-	-	-	13
NSCA	5	-	2	-	-	1	8
CSCS	*2*	-	*2*	-	-	-	4
*CSCS*D*	*2*	-	-	-	-	-	2
RSCC	*1*	-	-	-	-	-	1
UKSCA	6	-	-	-	-	-	6
CSP	-	-	-	7	-	-	7
ASCA	1	-	1	-	-	-	2
ASCA level 2	1	-	1	-	-	-	2
No professional accreditation	5	-	1	-	-	-	6
STA	-	2	-	-	-	-	1
STO	-	1	-	-	-	-	1
AIFI	-	-	-	1	-	-	1
BASES	1	-	1	-	-	-	2
NATA	1	-	-	-	-	-	1
APA	-	-	-	2	-	-	2
ESSA	1	-	-	-	-	-	1
CATA	-	-	-	-	1	-	1
BASRaT	-	-	-	-	-	1	1

Inclusion criteria for participation was any practitioner working with athletes in which a specific focus of their training was the reduction of risk factors associated with HSI and/or hamstring training with the aim of enhancing athletic performance. Given the diverse range of qualifications, job titles and accreditations across the globe, the survey did not aim to recruit any one specific practitioner.

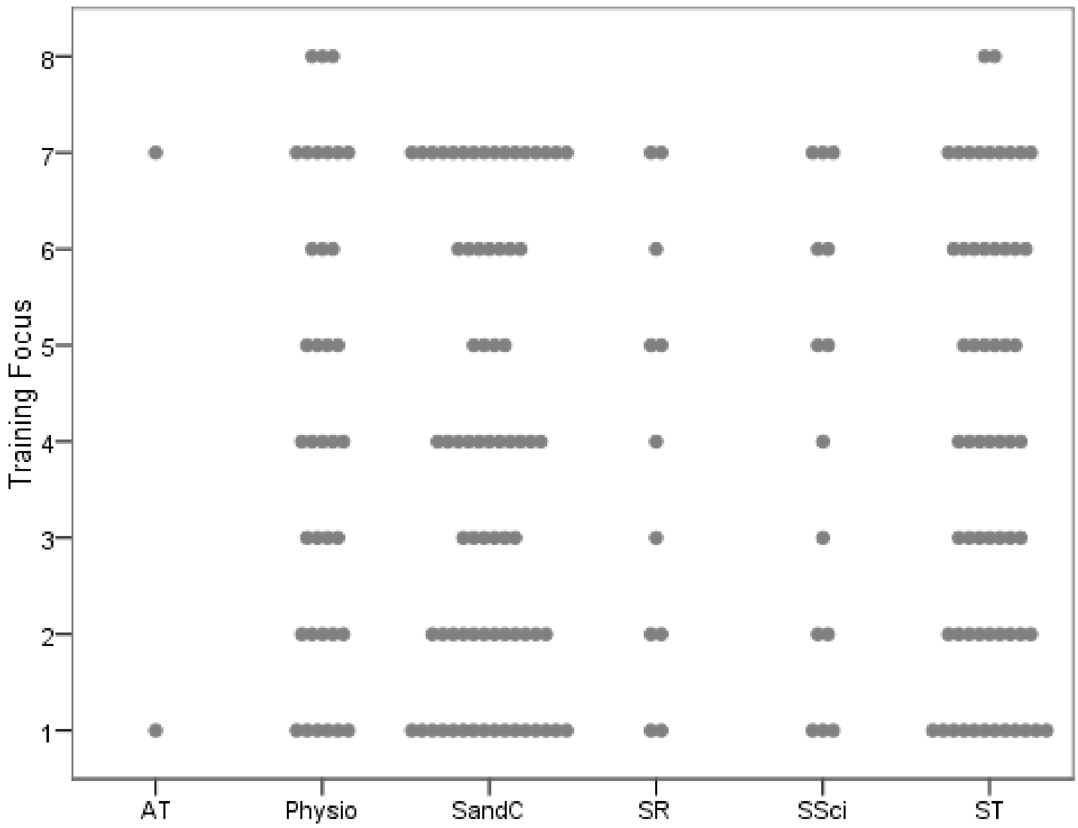


Figure 3-1 Dot plot illustrating training focuses sorted by each profession. 1 = Injury Prevention / Injury Risk Reduction; 2 = Increase Maximal Strength; 3 = Increase Strength Endurance; 4 = Increase Muscle Fascicle Length; 5 = Muscle Hypertrophy; 6 = Increase Flexibility; 7 = Enhanced Athletic Performance; 8 = No Specific Hamstring Training Focus. AT = athletic therapist; Physio = physiotherapist; SandC = stregnth and conditioning coach; SR = sports rehabilitator; SSci = sports scientist; ST = sports therapist.

Given that responsibilities can be non-uniform across job roles due to factors including, but not limited to the MDT, athlete level, time with athletes, professional biases / beliefs and training focuses at a given part of the training cycle, participants were asked to list the focuses of their training with their athlete groups. Understandably, training focus was varied and often broad in its scope across most practitioners. Therefore, the range of training focuses is presented as a dot plot (FIGURE 3-1), with each individual dot representing a response to a particular training focus.

Chapter 3.2.3 Statistical Analyses

All survey responses were exported from Google Forms to Microsoft Excel for coding of responses. Fixed response questions were analysed using frequency analysis in Jamovi (version 2.2.5). Differences in weekly NHE repetitions were calculated using two separate paired samples t-test to compare (a) the upper limit of weekly NHE repetitions and (b) the lower limit of weekly NHE repetitions identified by practitioners. This was due to the Likert-style nature of the questions pertaining to the number of sessions, sets and repetition structures typically used by practitioners. For instance, if a practitioner stated that they typically programme 1-2 weekly sessions consisting of three to four sets of three to four NHEs, the upper end of weekly session volume was calculated as two weekly sessions of four sets of four NHE repetitions (2*4*4 = 32 weekly NHEs) whereas the lower end was calculated as 1*3*3 = 9 weekly NHEs. Prior to the paired samples-test, assumptions of equal variances were checked and assumed through the Levene's test for homogeneity of variance using IBM SPSS (version 25). The same process of analysing upper and lower limits of weekly training repetitions was followed for non-NHE-based resistance training exercises magnitude of effect between off-season and in-season weekly resistance training repetitions was calculated and presented using https://estimationstats.com (Ho et al., 2019) with magnitude of difference expressed as Hedge's *g* given the unequal number of responses between off-season and in-season. Magnitude of effect was interpreted on the following scale: *trivial* ≤0.19; *small* 0.20 – 0.59; *moderate* 0.60 – 1.19; *large* 1.20 – 1.99; *very large* ≥2.00.

Open-ended questions were analysed using a six-staged thematic analysis as described by Braun and Clarke (Braun & Clarke, 2006). The stages included: (1) familiarisation with data; (2) generating initial codes; (3) searching for themes; (4)

reviewing themes; (5) defining and naming themes; (6) producing the report. Stages 2-6 of the thematic analyses were conducted in NVivo 12 Plus for Windows (QSR International).

Chapter 3.3 Results

3.3.1 HSR Practices

All S&C coaches, sports scientists, sports rehabilitators and athletic therapists reported that they programme high-speed running sessions during the off-season, with 64.3% and 70.0% of sports therapists and physiotherapists reporting that they programme HSR sessions during the off-season, respectively.

Table 3-2 Frequency of survey responders that programme high-speed running sessions during the off-season, grouped by profession.

	Profession						
Prescribe HSR Off-Season?	**Strength and Conditioning Coach**	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Athletic Therapist**	**Sports Rehabilitator**	**Total**
Yes	17	9	3	7	1	2	39
No	-	5	-	3	-	-	8

Of those that reported that they programme HSR sessions during the off-season, 23 provided an indication of the approximate total HSR session distance covered during a typical off-season session for their athletes. Of the 23, 56.5% stated that the typical total session distance covered at HSR would be 100 – 500 m with 21.7% of responders programming session distances of 500 – 1000 m and 17.4% and 4.3% programming session distances of 1000 – 1500 m and ≤100 m, respectively.

Table 3-3 Frequency of off-season HSR session distances programmed, grouped by profession

Session HSR Distance (m)	Profession						
	Strength and Conditioning Coach	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Athletic Therapist**	**Sports Rehabilitator**	**Total**
≤100	1	-	-	-	-	-	1
100-500	4	3	1	4	-	1	13
500 - 1000	4	-	-	1	-	-	5
1000 - 1500	2	1	-	-	-	1	4

All sports scientists, sports rehabilitators and the athletic therapist reported that they prescribe HSR sessions during the competitive season, whereas 78.6%, 70% and 94.1% of sports therapists, physiotherapists and S&C coaches reported prescribing in-season HSR sessions, respectively.

Table 3-4 Frequency of survey responders that programme high-speed running sessions during the in-season, grouped by profession.

Prescribe HSR In-Season	Profession						
	Strength and Conditioning Coach	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Athletic Therapist**	**Sports Rehabilitator**	**Total**
Yes	16	11	3	7	1	2	40
No	1	3	-	3	-	-	7

23 of the responders provided an approximation of the typical programmed session HSR distances in-season, of which 65.2% of practitioners programmed a typical session distance between 100-500 m, with 28.1% programming session distances of 500-1000 m with 1 S&C coach programming session distances of 1000-1500 m for

senior AFL athletes. One sports therapist indicated session distances >1500 m with professional soccer players, however this was noted as ‘total’, so it is possible that this is accumulative over conditioning and sport-specific sessions.

Table 3-5 Frequency of in-season HSR session distances programmed, grouped by profession

	Profession						
HSR Session Distances (m)	**Strength and Conditioning Coach**	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Athletic Therapist**	**Sports Rehabilitator**	**Total**
100-500	7	4	1	2	-	1	15
500-1000	4	-	-	1	-	1	6
1000-1500	1	-	-	-	-	-	1
>1500	-	1	-	-	-	-	1

Of those that programme HSR sessions as part of their current role, 16 practitioners did not provide a numerical approximation of HSR session distances during the off-season and 17 did not provide numerical HSR session distances in-season. Thematic analysis of the descriptions of these non-numerical responses indicated that during the off-season practitioners tend to give more emphasis on speed preparation and drills with a specific focus on acceleration and deceleration. Response themes also focused a greater volume of HSR or frequency of HSR exposures during the week in comparison to in-season practices. Several practitioners indicated that they focus on approximately three to six maximal efforts or efforts building to maximal velocity in-season, whereas several practitioners indicated approximately four to ten efforts during the off-season. While HSR weekly frequencies and the thresholds for identifying HSR are reported in further in the current chapter subsection, there was a clear thematic trend to the utilisation of lower intensity bouts during the off-season.

Practitioners indicated that 'HSR' sessions may include bouts of 50-75% of maximal velocity, with some practitioners identifying that they still ensure a minimum dose of 2 efforts exceeding 90% of maximal velocity or maximal effort. On the other hand, in-season HSR sessions were more associated with practitioners indicating bouts exceeding 80% of maximal velocity or maximal effort.

Further, there was also an indication of programming of HSR sessions based on individual match-play demands. For instance, one practitioner identified that they aim to ensure that athletes do not exceed 80% of their match-day HSR volume during in-season training whereas another indicated that their HSR volume would approximate 20% of the athlete's match-day HSR exposure. With regards to the off-season two practitioners also highlighted that HSR sessions would be programmed to approximately 10-20% of total match-play HSR exposures.

Table 3-6 Weekly exposures to off-season HSR sessions grouped by profession.

	Profession					
Weekly HSR Exposure (off-season)	**Strength and Conditioning Coach**	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Sports Rehabilitator**	**Total**
0-1	2	-	-	-	-	2
1-2	9	9	2	9	2	31
2-3	1	-	1	-	-	2
3-4	5	1	-	-	-	6

During the off-season, of the 41 responders that programmed HSR sessions, 75.6% programmed 1-2 sessions per week, with 14.6% programming 3-4 weekly sessions with the remaining 9.8% distributed equally between zero to one and two to three sessions per week.

Table 3-7 The weekly exposures to in-season HSR sessions grouped by profession.

Weekly HSR Exposure (in-season)	Profession					
	Strength and Conditioning Coach	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Sports Rehabilitator**	**Total**
0-1	-	-	1	-	-	1
1-2	14	9	-	7	2	32
2-3	2	-	-	-	-	2
3-4	1	1	2	2	-	6

A very similar trend was observed with regards to in-season, 78.0% of practitioners that programmed HSR sessions, programmed one to two weekly sessions, with 14.6% programming two to four weekly sessions and 4.9% and 2.4% programming two to three and zero to one weekly sessions, respectively.

When questioned what practitioners considered as ‘high-speed’ during programmed HSR sessions, all of those that stated that they do programme sessions, identified a target which they would use for high-speed, however there was a mixture of specific velocity thresholds and perceived intensities. For those using specific HSR velocity thresholds, all indicated a minimum of 5.5 – 6.0 $m{\cdot}s^{-1}$ (19.8 – 21.6 $km{\cdot}h^{-1}$) with sprinting velocities between 7.5 – 8.0 $m{\cdot}s^{-1}$ (27.0 – 28.8 $km{\cdot}h^{-1}$). On the other hand, those that indicated the use of a perceived intensity, such as a percentage of maximal, there was a larger degree of variability with some practitioners indicating values as low as 50-75% of maximal, but largely practitioners seemed to advocate the use of perceived thresholds of ≥85% of maximal effort.

Table 3-8 Data obtained from HSR sessions grouped by profession.

Data Obtained on HSR Sessions	Strength and Conditioning Coach	Sports Therapist	Sports Scientist	Physiotherapist	Sports Rehabilitator	Athletic Therapist	Total
Session distance	14	10	-	2	5	1	32
Perceived Intensity	10	8	1	1	4	-	24
None	1	3	-	1	1	-	6
Velocities/Accelerations (global positioning system [GPS] derived)	11	5	-	2	4	1	23
Velocities/Accelerations (timing gate/timing derived)	4	2	-	-	4	1	11

From all responders, it was identified that only 6 professionals identified that they do not collect any objective data from HSR sessions. While 4 of these participants identified that they do not actively lead HSR sessions in their current job role, two practitioners (one sports scientist and one strength and conditioning coach) identified that they do lead HSR sessions within their role, but do not collect objective data from the session. Across all professions other than the single athletic therapist, it was clear that the majority of practitioners obtain more than one source of objective data from their HSR sessions, with total sessions distance, GPS derived velocities and/or accelerations and athlete perceived intensity as the most commonly utilised methods.

When asked '*how would you best describe the primary focus of your high-speed running sessions?'*, 43 practitioners responded, which included three practitioners which had not previously stated that they run HSR sessions, however during analysis of these responses there was limited information provided such as 'football conditioning', 'to meet demands of sport' and a slightly more detailed response of 'to offer a stimulus similar to that of maximal match-day exertion'. As these three practitioners had not previously stated they programme or lead HSR sessions or indicated a response in questions pertaining to session volume or frequency, it is unclear whether the information provided was a general overview of what they consider to be an important focus of HSR training, or if they were referring to their approach to HSR training during rehabilitation as the responses were provided by two physiotherapists and one sports therapist.

Of those practitioners that had previously indicated that they programme and/or lead HSR sessions, the overwhelming theme pertaining to the primary focus of HSR sessions was to ‘build capacity’, ‘provide exposure to maximal running efforts’ and to ‘reduce injury risk’. Further, there was a common theme of combining technical coaching cues relating to front side mechanics, technical proficiency and either mimicking or preparing the athlete for the volume of HSR efforts they would typically be exposed to during match-play. To a lesser extent, there was also reference made from some practitioners to exposing the athlete to multidirectional movements, external cues, and a competitive environment within the session.

Table 3-9 Frequency distribution of typical time period allowed between HSR sessions grouped by profession.

	Profession						
Time Between HSR Sessions	**Strength and Conditioning Coach**	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Athletic Therapist**	**Sports Rehabilitator**	**Total**
24 hours	1	1	-	-	-	-	2
36 hours	2	3	-	-	-	-	5
48 hours	12	7	3	3	1	2	28
72 hours	-	1	-	3	-	-	4
>72 hours	-	-	-	1	-	-	1

With regards to the typical time period between HSR sessions, 39 practitioners provided a numerical approximation, with 71.8% of practitioners indicating that they allow 48 hours between HSR sessions. four practitioners provided a non-numerical description of their typical approach, with one practitioner indicating that the time-frame can vary between 24-36 hours, given that not all sessions target maximal speed, indicating that Wednesday sessions generally focus on ‘lactate work and moderate intensity interval training’, with Thursday focusing on top speed and Friday focusing on ‘low level’ aerobic training. One further practitioner indicated that the time-period was typically 48 hours, but that they tend to time short sprints to establish ‘readiness’. The same practitioner also identified that they use these times to establish whether the athlete is ready for intense training on that day but did not identify a specific threshold which the athlete would be required to achieve to be considered ready for intense training exposure. One S&C coach working with AFL athletes indicated that timing of HSR sessions which focus on >80% maximal velocity with a focus on reduction of HSI risk are usually positioned around match day minus three or four.

3.3.2 Resistance Training Practices

All strength and conditioning coaches, sports scientists and sports rehabilitators identified that they programme and / or lead hamstring focused resistance training sessions during the off-season as well 71.4% of sports therapists and 90% of physiotherapists. The single athletic therapist identified that they do not programme / lead resistance training sessions during the off-season.

Table 3-10 Frequency of survey responders that programme resistance training sessions during the off-season, grouped by profession.

Programme Off-Season Resistance Training?	Profession						
	Strength and Conditioning Coach	Sports Therapist	Sports Scientist	Physiotherapist	Athletic Therapist	Sports Rehabilitator	Total
Yes	17	10	3	9	-	2	41
No	-	4	-	1	1	-	6

From the 41 practitioners that identified that they programme and / or lead hamstring focused resistance training sessions during the off-season, 80.5%, stated that they would typically include one to two sessions per week. With the remaining 19.5% stating a higher weekly training frequency of three to four sessions. From the 19.5% stating that they programme and / or lead three to give resistance training sessions per week, all but one worked in intermittent intensity-based team sports, with one working in athletics and combat sports.

Table 3-11 Frequency distribution of number of weekly hamstring focused resistance training sessions programmed during the off-season, grouped by profession.

Weekly Resistance Training Sessions	Profession					
	Strength and Conditioning Coach	Sports Therapist	Sports Scientist	Physiotherapist	Sports Rehabilitator	Total
1-2	13	8	2	8	2	33
3-4	4	2	1	1	-	8

The typical off-season set and repetition schemes for the NHE varied across practitioners, with no clear pattern of approach between professions. Therefore, frequency counts of typical set and repetition schemes are displayed in FIGURE 3-2 with the highest count of 12 practitioners opting for an approach of four sets of four repetitions, followed by ten counts of four sets of six repetitions. From FIGURE 3-2, it is clear to see that most practitioners seem to adopt schemes based on four sets, however eight practitioners did identify that they adopt lower set schemes ranging from two sets of four repetitions to two sets of six repetitions. At the upper end of the scale, one practitioner identified the use of four sets of ≥12 repetitions of the NHE. When considering the data points presented in FIGURE 3-2 it should be noted that the questions in the survey pertaining to NHE repetitions and sets were presented on a Likert-type scale, in which practitioners could select a small range e.g., one to two sets, three to four sets, five to six sets and likewise for repetitions. Practitioners could also select an option of 'other' and provide a more detailed response if they felt that the scaled options did not best represent their typical practice. Therefore, for brevity in presentation, the data points presented represent the upper end of the scale for each practitioner response. Some practitioners provided some additional qualitative information here for instance one practitioner identified that their typical approach is one to two sets, but some athletes may increase to three sets, while another stated that they take a progressive approach to programming the NHE over a six-week period starting with three to four sets of four repetitions. Finally, one practitioner did not provide an indication of set and repetition structure but did indicate that their NHE programming is informed by isokinetic testing, but unfortunately did not elaborate further on this statement.

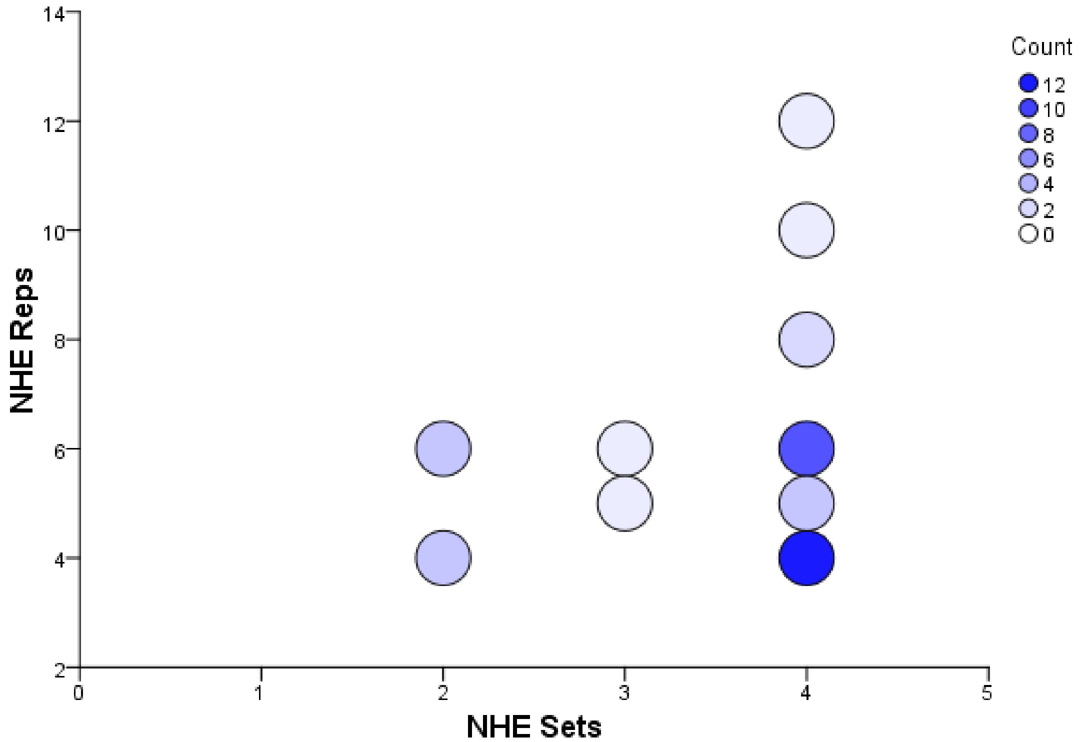


Figure 3-2 A binned scatterplot displaying the frequency counts for repetition (vertical axis) and set (horizontal axis) schemes when programming the NHE during the off-season. The lightest grey shading denotes the fewest counts (two) through to the darkest shaded blue denoting the highest number of counts (twelve).

91.5% of practitioners identified that they programme and / or lead in-season hamstring focused resistance training programmes which consisted of 94.1% of S&C Coaches, 85.7% of sports therapists, all sports scientists, sports rehabilitators and the single tthletic therapist and 90% of physiotherapists.

Table 3-12 Frequency of survey responders that programme resistance training sessions in-season, grouped by profession.

Programme In-Season Resistance Training?	Profession						
	Strength and Conditioning Coach	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Athletic Therapist**	**Sports Rehabilitator**	**Total**
Yes	16	12	3	9	1	2	43
No	1	2	-	1	-	-	4

Of the 43 practitioners that programme / lead in-season resistance training sessions, 86.0% identified that they typically include one to two weekly sessions. This indicates a small reduction in resistance training frequency from the off-season, from 19.5% of practitioners including three to four weekly sessions in the off-season, down to 14.0% in-season, however the use of the 'other' option with reference to in-season, meant that all responses >2 weekly sessions, included the possibility of three or more sessions, which may indicate variance in training practices in-season likely due to fixture cycles, given that most of the practitioners that indicated three or more sessions worked in soccer in the United Kingdom, which can have large variations fixture congestion, particularly during the winter months (Julian et al. 2021).

Table 3-13 Frequency distribution of number of weekly hamstring focused resistance training sessions programmed in-season, grouped by profession.

	Profession						
Weekly In-Season Resistance Training	**Strength and Conditioning Coach**	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Athletic Therapist**	**Sports Rehabilitator**	**Total**
1-2	15	10	3	7	-	2	37
2-3	1	-	-	-	-	-	1
3-4	-	1	-	2	1	-	4
3-5	-	1	-	-	-	-	1

The typical repetition and set structures when programming the NHE in-season were largely varied (FIGURE 3-3) across practitioners, with two sets of four repetitions and four sets of four repetitions highlighted as the most common responses (ten counts each). However, as these set and repetition structures are presented as the upper end of practitioner responses, the weekly NHE repetitions (sessions*sets*repetitions) for the upper and lower end of practitioner responses are presented in FIGURE 3-3 and 3-4, respectively.

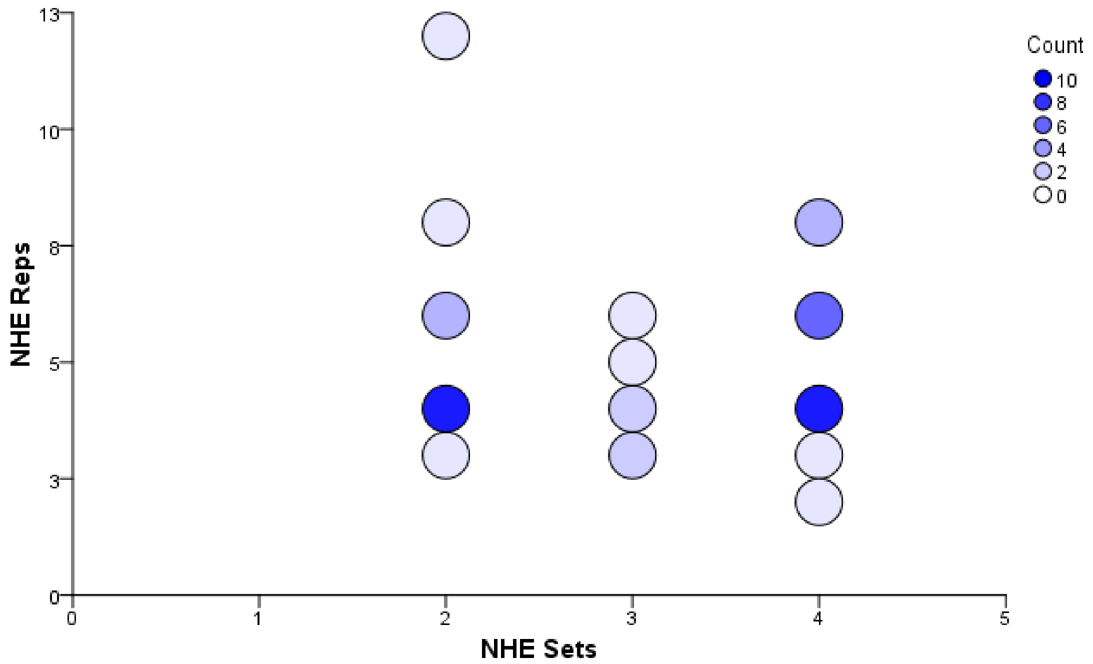


Figure 3.3 A binned scatterplot displaying the frequency counts for repetition (vertical axis) and set (horizontal axis) schemes when programming the NHE in-season. The lightest grey shading denotes the fewest counts (two) through to the darkest shaded blue denoting the highest number of counts (ten).

The upper-end of the number of weekly NHE repetitions during the off-season and in-season are presented in FIGURE 3-3. There was a small but non-significant (g = -0.44; p = 0.100) difference between the mean number of off-season (45.5 ± 23.4 weekly NHE repetitions) and in-season (37.5 ± 25.5 weekly NHE repetitions).

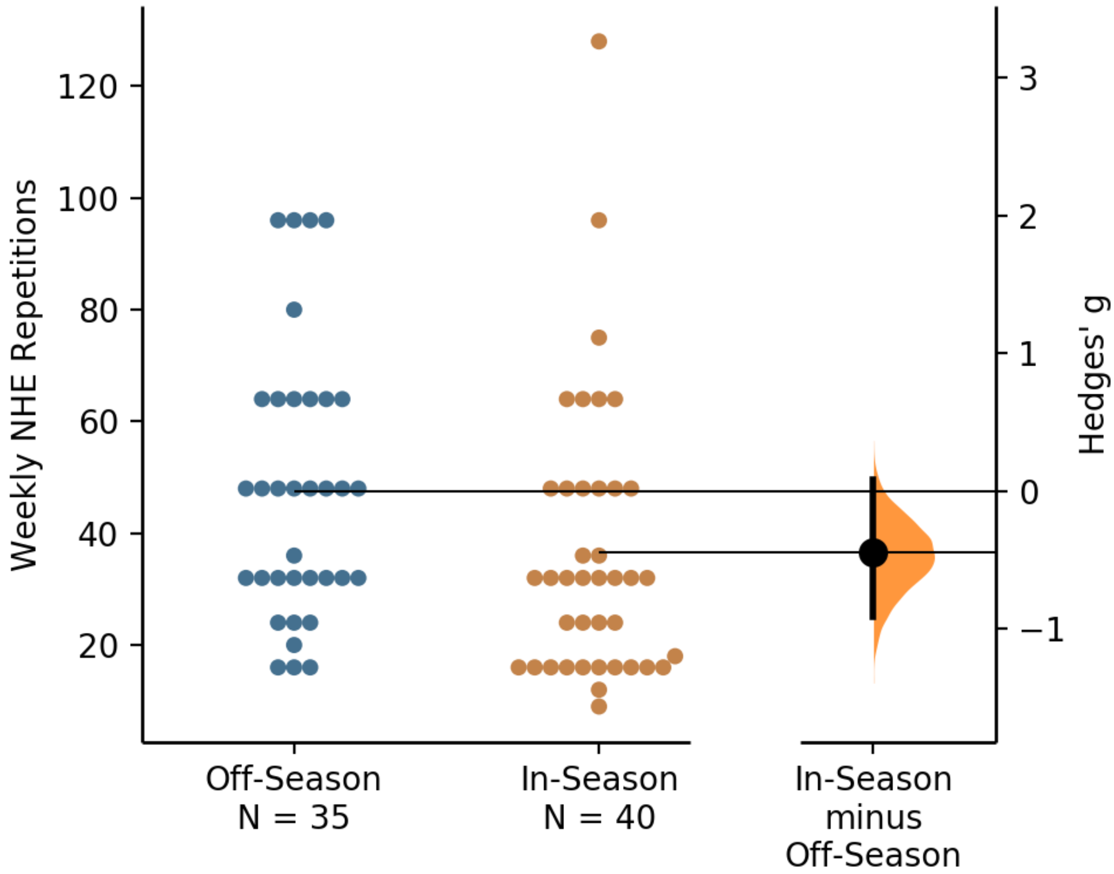


Figure 3-3 A Gardner-Altman estimation plot illustrating the upper end of weekly number of NHE repetitions during the off-season (blue) and in-season (orange). Both groups are plotted on the left axes, with the mean difference and magnitude of difference are plotted on floating axes on the right. The mean magnitude of difference is depicted as a black dot, with the 95% confidence interval indicated by the ends of the vertical bar.

Furthermore, when considering the lower end (FIGURE 3-4) of the typical weekly NHE repetitions reported by practitioners, differences in weekly repetition volume was also small but not statistically significant (g = -0.42; p = 0.140) decrease in the number of weekly NHE repetitions in-season (12.7 ± 12.3 weekly NHE repetitions) compared with off-season (17.3 ± 12.2 weekly NHE repetitions).

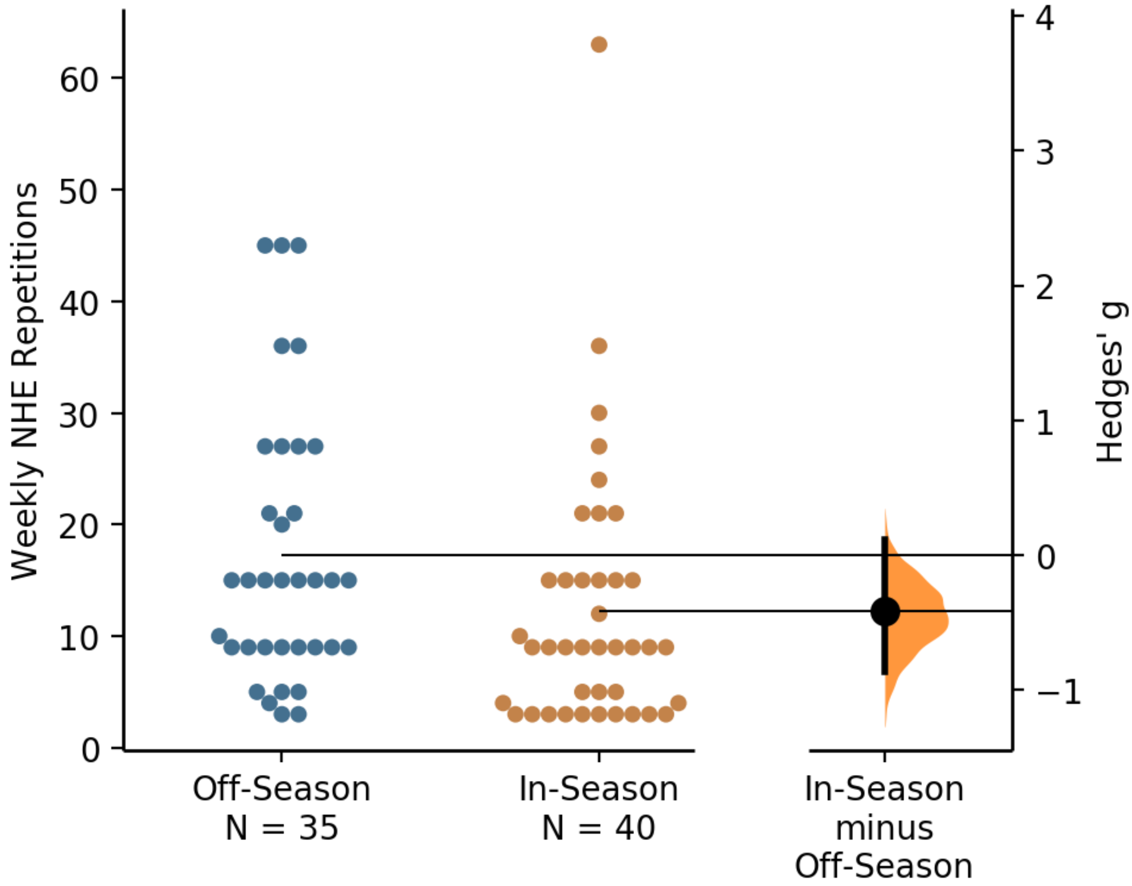


Figure 3-4 A Gardner-Altman estimation plot showing the lower end of weekly number of NHE repetitions off-season (blue) and in-season (orange). Both groups are plotted on the left axes, with the mean difference and magnitude of difference are plotted on floating axes on the right. The mean magnitude of difference is depicted as a black dot, with the 95% confidence interval indicated by the ends of the vertical bar.

Practitioners were asked to identify any resistance training exercises they use excluding the NHE (TABLE 3-14). There was a broad range of exercises identified, with the RDL as clearly the most commonly utilised non-NHE resistance training exercise and the only exercise that was identified as being used across all six professions included in the survey. The glute bridge and variations on bridges (such as SL bridges, hamstring catches and knee slides) were also used frequently across professions.

Table 3-14 shows the frequency distribution of non-NHE resistance training exercises grouped by profession. RDL = Romanian Deadlift; Ham = Hamstring; KB = Kettlebell; SL = Single Leg; Askling L = Askling's 'L' Protocol; PNF = Proprioceptive Neuromuscular Facilitation.

	Profession						
Exercises	**Strength and Conditioning Coach**	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Athletic Therapist**	**Sports Rehabilitator**	**Total**
RDL	11	7	1	1	1	1	22
Glute Bridge	5	2	-	2	-	-	9
Glute Ham Raise	2	1	-	4	-	1	8
KB Swing	1	1	-	1	-	-	3
SL Glute Bridge	1	2	-	1	-	-	4
SL RDL	4	3	-	3	1	1	12
SL Hamstring Catch	1	1	-	-	-	-	2
Hip Thrust	3	2	-	-	-	1	6
Knee Slide	2	4	-	3	-	1	10
SL Knee Slide	1	1	-	-	-	-	2
Good Morning	3	-	-	1	-	-	4
Tantrum	1	1	-	1	-	-	3
Hamstring Catch	3	-	-	1	-	-	4
Leg Curl	-	3	1	-	-	1	5
Deadlift	2	3	-	2	-	-	7
Long Lever Glute Bridge	3	2	-	1	-	-	6
Drop Catches	1	-	-	1	-	-	2
Bulgarian Split Squat	-	2	-	-	-	-	2
Hip Hinge	2	-	-	-	1	-	3
Askling L	1	-	-	2	-	-	3
Fly Wheel RDL	2	-	-	1	-	-	3
SL Hip Hinge	1	-	-	-	-	-	1
Bosch Hold	-	1	-	-	-	-	1
Roman Chair Extension	1	-	-	-	-	-	1
Pull Derivatives	1	-	-	-	-	-	1
Lunge	1	-	-	-	-	-	1
Snap Down	1	-	-	-	-	-	1
PNF Hold	1	-	-	-	-	-	1
IKD Concentrics	-	-	-	1	-	-	1
SL Long Lever Glute Bridge	1	-	-	-	-	-	1
Fly Wheel Leg Curl	1	-	-	-	-	-	1

With regards to the lower end (FIGURE 3-5) of typical weekly repetitions of non-NHE resistance exercises between off-season and on-season, there was a small, but non-significant (g = -0.55; p = 0.073) reduction in volume in-season (18.94 ± 11.74 weekly non-NHE repetitions) compared with off-season (27.71 ± 22.07 weekly non-NHE repetitions).

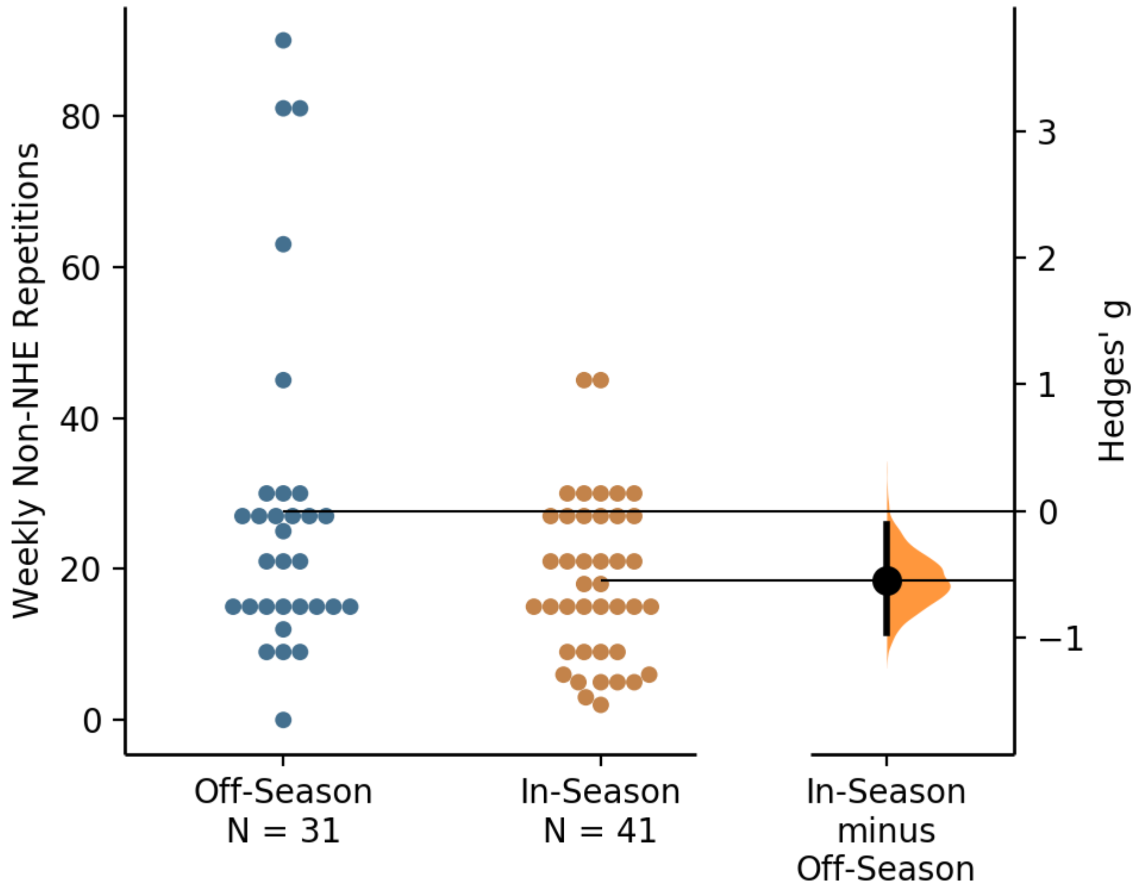


Figure 3-5 A Gardner-Altman estimation plot showing the lower end of weekly number of non-NHE repetitions off-season (blue) and in-season (orange). Both groups are plotted on the left axes, with the mean difference and magnitude of difference are plotted on floating axes on the right. The mean magnitude of difference is depicted as a black dot, with the 95% confidence interval indicated by the ends of the vertical

When considering the upper end (FIGURE 3-6) of the reported typical weekly non-NHE resistance training repetitions, there was a moderate and significant (g = -0.70;

p = 0.014) reduction in volume during the in-season (55.55 ± 26.60 weekly non-NHE repetitions) compared with off-season (77.42 ± 46.84 weekly non-NHE repetitions).

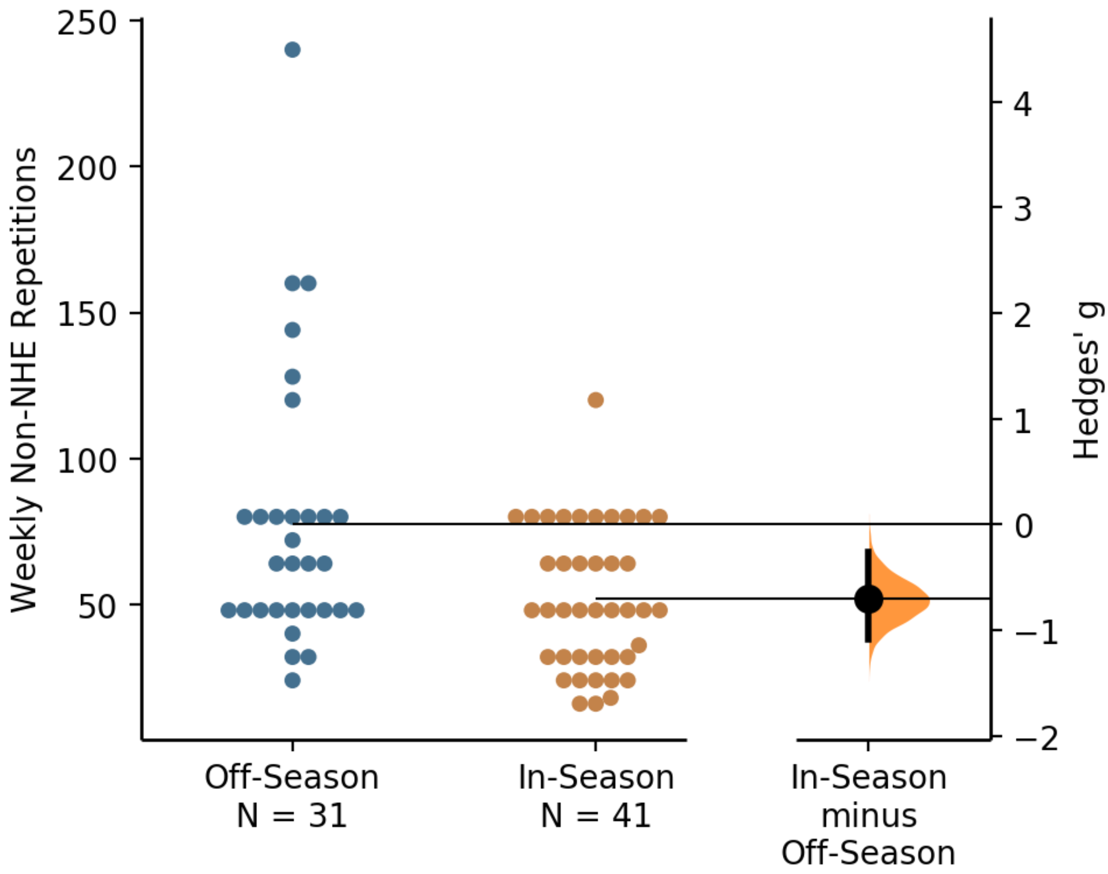


Figure 3-6 A Gardner-Altman estimation plot showing the upper end of weekly number of non-NHE repetitions off-season (blue) and in-season (orange). Both groups are plotted on the left axes, with the mean difference and magnitude of difference are plotted on floating axes on the right. The mean magnitude of difference is depicted as a black dot, with the 95% confidence interval indicated by the ends of the vertical

From responses relating to methods used by practitioners to select training load during non-NHE-based resistance training (TABLE 3-15), it was clear to see that the majority of practitioners make their assessment based on movement quality under load (31 total responses), with several practitioners also reporting in the additional information that they prioritise movement quality over load. In addition to movement quality, practitioners frequently opted for load selections based on repetition maximum or predicted repetition maximum (13 responses each) and 20 responders indicated that they make their selections based on rate of perceived exertion (RPE) of Likert scales.

15 responders indicated that loads are selected by the athletes, however as several of the responders that indicated that they use repetition maximum, RPE/Likert scales, and repetition maximum/predicated repetition maximum as well as athlete selected loads, it is possible that athletes select loads within a range of a previously determined maximum and adjust accordingly based on the RPE/Likert scale during a given session.

Table 3-15 Frequency distribution of methods used to select resistance training load grouped by profession.

Methods Used	Profession						
	Strength and Conditioning Coach	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Athletic Therapist**	**Sports Rehabilitator**	**Total**
Repetition maximum	5	4	1	3	-	-	13
Predicted repetition maximum	6	4	-	2	-	1	13
Rate of perceived exertion / Likert scale	9	5	3	2	1	-	20
Movement Quality	14	7	2	6	1	1	31
Subjective / guess	4	-	-	2	-	-	6
Trial and error	3	4	1	1	-	1	10
Velocity-based (e.g. accelerometer/linear position transducer)	7	-	1	2	-	1	11
Train to momentary muscle failure	-	2	-	-	1	1	4
Athlete selected	3	8	1	2	-	1	15
Repetitions in reserve	3	-	-	-	-	-	3
Percentage of body weight	1	-	-	1	-	-	2
Position specific	-	1	-	-	-	-	1

Methods used to assess athlete training adaptations are reported in TABLE 3-16. Thirty practitioners identified that they assess adaptations in eccentric hamstring strength, with 28 stating that they use isometric measures of hamstring strength, with only 12 opting to assess concentric hamstring strength. Other commonly used tests included hamstring flexibility (24 responses) and maximal running velocity (25 responses). Only seven practitioners reported that they assess muscle architectural adaptation.

Table 3-16 Frequency distribution of methods used to assess training adaptation grouped by profession.

	Profession						
Tests Used	**Strength and Conditioning Coach**	**Sports Therapist**	**Sports Scientist**	**Physiotherapist**	**Athletic Therapist**	**Sports Rehabilitator**	**Total**
Eccentric hamstring strength	10	8	2	8	-	2	30
Isometric hamstring strength	7	10	-	9	-	2	28
Hamstring muscle architecture	3	1	-	2	-	1	7
Repetition maximum	3	3	1	1	-	2	10
Running technique	4	2	-	3	1	-	10
Kinematic analysis	4	2	-	1	1	2	10
Hamstring flexibility	8	9	1	5	1	-	24
Strength-endurance	4	5	-	3	-	2	14
Maximum running velocity	10	6	2	5	-	2	25
Concentric hamstring strength	1	6	1	3	1	-	12
Running force-based assessment	1	1	-	2	-	2	6
Horizontal force-velocity	2	-	-	-	-	1	3

3.4 Thematic Analysis of Open-Ended Questions

Practitioners were asked a number of open-ended questions to explore individual perceptions of training for the mitigation of HSI and development of athletic performance. The thematic analysis of these responses is presented herein.

Question: *'What is your current understanding of the modifiable risk factors for hamstring strain injury?'*

Table 3-17 shows the coded responses relating to the open-ended question of understanding of modifiable risk factors for HSI, the frequency count of coded responses and samples of practitioner qualitative narratives.

Understanding of HSI risk factors	*Frequency of Occurrence*	*Sample of Practitioner Narratives*
Eccentric Strength	*17*	*"Lower levels of eccentric hamstring strength (along with other factors) have been shown to increase risk of injury."* *"Weak hamstrings measured during the NHE has been shown to contribute to injury risk."* *"I've had athletes with hamstring pulls before (it was our most common injury in 2020). We did Nordic Hamstring curls 4-5 sets of 5+ reps 3-4 times per week. I think that volume was just too high, especially with their high volumes of sprint and baseball-specific training added on top of it."*
Training Load	*15*	*"Load management and fatigue-monitoring are the two biggest factors I know of."* *"Considering load when combined with objective data Reducing HSI risk factors by exposing players to HSD/>90% max speed"* *"Monitoring weekly exposures to HSI to identify peaks in acute training volume and adjusting training to manage."*

Fascicle Length	*10*	*"Fascicle length is important. Short and weak = bad news."* *"Two-week window where fascicle length adaptation will then reduce."*
Flexibility	*6*	*"Reduced flexibility can be a risk for injury"*
Previous HSI	*3*	*"A history of previous HSI can increase risk of future injury, although this can be mitigated to some extent through training"*
Age	*3*	*"Age – we've observed a few more injuries in our older players (>30) than in the younger players in the squad"*
No Knowledge	*3*	*"Minimum to none."* *"Not heard the term."*
Running Mechanics	*2*	*"Adapted to prevent injury (e.g., knees not going beyond big toe in sprint patterns or jump patterns)."*
Isometric Strength	*1*	*No additional comment provided*
No Predictive Value	*1*	*"No predictive validity or model available to predict injury."*

The majority of practitioners identified that they have an appreciation for the multifactorial nature of HSI risk. As presented in TABLE 3-17, the key risk factors identified by practitioners were eccentric hamstring strength, training load and FL. This seems to offer support to the data presented in TABLE 3-18, which highlights that the majority of practitioners surveyed conduct regular testing of eccentric hamstring strength and load monitoring. On the other hand, much fewer practitioners conduct regular assessment of FL, which is likely due to a lack of accessibility given the monetary cost of 2-B ultrasound machines and the specialist training required to accurately conduct such assessments. Although seven practitioners identified a lack of facilities as a key limiting factor to their current practice (presented in TABLE 3-20), with several practitioners stating that they considered a lack of access to strength testing facilities as a limiting factor, only one practitioner stated that they considered a lack of access to ultrasound as a limiting factor. Given some of the limitations and criticisms of methods used (Ripley et al., 2022) to estimate BFLH FL, it is possible that practitioners do not consider lack of ultrasound testing as a limiting factor due to potential measurement error. However, it is also possible that given the evidence that increases in knee flexor strength from eccentric training seem to be associated with increases in FL (Cuthbert et al., 2020; Ripley et al., 2021), practitioners may be satisfied that a measured increase in knee flexor strength may likely be associated with increased FL, even if it is not something they have actively measured.

Question: '*What do you believe to be the most important intervention strategy/strategies to reduce incidence and/or risk of hamstring strain injury?'*

Table 3-18 shows the coded responses relating to the open-ended question of understanding of what practitioners consider as the most important interventions to mitigate HSI risk, the frequency count of coded responses and samples of practitioner qualitative narratives. Where some category responses are similar in nature, subcategories of codes have been presented (for instance 'match-day specific HSR as a subcategory code for Exposure to HSR. Categories and sub categories have therefore been numbered for clarity.

Intervention Strategies	*Frequency of Occurrence*	*Sample of Practitioner Narratives*
1. Exposure to HSR	*16*	*"Exposure to high-speed running volume and maximal velocity efforts."* *"Exposure to >90% max speed x2 weekly."*
1.1 Match-Day Specific HSR	*4*	*"Regular exposure to matchday HSR Session Distances."* *"Load exposure equal to game specific ranges."*
2. General Strength Training	*11*	*"I believe a focus on hip dominant hamstring exercises are the most important strategies to reduce hamstring strain incidence due to preferential activation of the Biceps Femoris."* *"Multiplanar Strengthening."*
2.1 Eccentric Strength Training	*13*	*"Strength based interventions, specifically eccentric in nature."*
2.2 Isometric Stregnth Training	*4*	*"We also focus on end-range isometrics (PNF style hamstring stretches) and eccentric overload (NHE). I believe these help the hamstring handle the immense stretching/eccentric forces found in sprinting or in sports."*

2.3 Concentric Strength Training	*2*	*“Combined series of resistance training (isometric, concentric & eccentric.”*
3. Managing Exposure / Load Monitoring	*12*	*“Monitoring fatigue through measuring a Countermovement jump, 12 inch drop depth jump RSI or short 10-20 yd sprint prior to training. We don’t train at high intensity if they cannot achieve within 5% of their peak, and I think training in a non-fatigued state is crucial for preventing injury.”* *“Not over exposing athletes to match days or training sessions.”* *“Not over exposing athletes to match days or training sessions if their long lever hamstring strength is reduced when compared to the norm or when compared bilaterally.”*
4. Technique Modification	*5*	*“To reduce the risk of HSI there are a number of fundamental technique elements (may be similar across many movements) that could be adapted to prevent injury (e.g., knees not going beyond big toe in sprint patterns or jump patterns).”*
5. Flexibility & Mobility	*4*	*“Developing Hip Joint & Knee Joint Mobility / Flexibility.”*

6. Communication & Education	*4*	*“Managing a players risk and exposure through communication with S&C / technical coaching staff.”* *“Education to the players on how to treat them when it comes to DOMS or tightness.”*
7. Improving FL	*2*	*“Eccentric Loading to increase FL.”*
8. Recovery	*2*	*“Work to rest ratio, need an efficient work to build tolerance and enough recovery.”*
9. Compliance	*1*	*“NHE most effective, but compliance matters.”*
10. Deceleration Ability	*1*	*“Hamstrings with rapid hamstring deceleration/chaos work.”*

Interestingly, 15 practitioners identified training load, including exposures to HSR and the identification of acute peaks in training load as a key HSI risk factor, with 20 practitioners stating that they believe exposure to HSR or match-play specific HSR as a key strategy to mitigate HSI risk (TABLE 3-18). As seen in TABLE 3-16, 23 surveyed practitioners identified that they collect GPS data for the purposes of monitoring HSR exposures. On the other hand, as seen in TABLE 3-20 there is several themes that can be identified relating to the challenges associated with load monitoring and exposure to HSR within practice and within a MDT. Key themes emerged relating to the difficulties in coordinating load exposure and management within the MDT, for instance coaches and players ramping training sessions which may cause acute spikes in HSR exposure at a time within the training week which may increase the likelihood of an injurious event due to insufficient recovery from previous sessions or insufficient recovery time before the next planned exposure or match day. Additionally, several practitioners identified a lack of communication within the MDT (across support departments and sports coaches), which may lead to an ill-planned training week, or lead to unplanned training exposures, with one participant indicating that unplanned training sessions in their area of work may include anything from ten competition-based sprints to a three-mile run, both of which could significantly increase total weekly HSR exposure or total running volume.

While exposure to HSR may be a key method for reducing the risk of HSI which seems to be a belief of practitioners (although a greater number of training intervention and long-term athlete load monitoring studies are required to further better support this notion), the links between acute spikes in HSR load and the direct link between HSR and HSI mechanism (Duhig et al., 2016; Malone et al., 2017), it seems imperative from the findings of the current study, that MDTs (including sports coaches) must strive for better communication and forward planning to appropriately monitor and periodise HSR exposes across training mesocycles, which in-turn would hopefully allow MDTs to be proactive in their ability to adjust planned training exposures in response to the often chaotic reality of sport, particularly at the elite level in which fixture congestion and re-scheduling of fixtures may be commonplace.

Table 3-19 Coded responses relating to the open-ended question of understanding of practitioner approaches to compliance to hamstring training. the frequency count of coded responses and samples of practitioner qualitative narratives.

Compliance Strategy	*Frequency of Occurrence*	*Sample of Practitioner Narratives*
Elsewhere in Training Week	*15*	*"[The session component] is repeated later in the week in the off-season. In season it a modified session may be performed later in the week depending upon the athlete and what our fatigue monitoring is telling us (e.g., are we making them sore too close to a game or not)."* *"We will typically have a general plan of Nordic hamstring curl volume as well as other exercises' volume that we try to get done each week. So, if an athlete has to forgo an intense session due to fatigue, we will attempt to get the planned session done the next time they are not fatigued."* *"At some point in the week [the athlete] will catch up even if it is just a couple of sprints."*
Athlete Responsibility	*7*	*"At our level of rugby union, we do not have the structure to be able to monitor compliance of resistance training sessions. We place a large emphasis outside of the rehabilitation setting on players adhering to strengthening sessions in their own time."*

		"Usually, players are instructed to perform it at home." *"Just adapt and encourage players to double up sets on other exercises."*
Yes	*6*	*No additional information provided*
Micro-Dosed	*6*	*"My approach to compliance is to include hamstring maintenance as part of a pre/post session activity based around the athlete's regular gym routine/session."* *"Include exercises that helps to either hamstring strength, endurance or flexibility into warm up of all training, including sports training, so that missing a session or two will not be an issue."*
Dependant on Fixtures	*5*	*"Dependant on fixture schedules and when the session was missed may determine if only some of the missed work is completed, i.e., if it's close to match day they may only do part of the session missed, so a reduction in volume is given."* *"Incorporation into where the fatigue will not effect game related activity/"*

HSR > Resistance Training	*3*	*"If speed target missed eccentric exercise must be completed. If speed attained less concerned at missing resistance exercise."* *"Typically, if gym session(s) are dropped a greater focus will be spent on high-speed running to mitigate some potential loss of training (i.e. NHE)."*
Athlete Education	*2*	*"We educate our players that if they do not comply to S&C programmes, their chance of injury increases."*
Missed Opportunity	*2*	*"If possible, but typically that is just a missed opportunity."*
No – Due to Recovery	*1*	*"I do not catch up on missed sessions as adequate recovery time is needed before the next hamstring session."*
Underpinned by GPS	*1*	*"If possible, but players on live GPS so normally targets met."*

Better communication and forward planning within the MDT may well reduce incidence of future HSIs, however better athlete education also seems imperative to the long-term success of any strategy to improve training practices. Practitioners cited athlete compliance with training as well as some aspects of fear of adverse training effects such as DOMS as factors which currently limit their practice. While the likes of DOMS have previously been cited as potential limitations of eccentric resistance training

(Bahr et al., 2015) compliance with training interventions has also been found to be key in the success of training for the mitigation of HSI risk (Ripley et al., 2021).

Table 3-20 Coded responses relating to the open-ended question relating to the key challenges and limitations to mitigating HSI factors, the frequency count of coded responses and samples of practitioner qualitative narratives.

Compliance Strategy	*Frequency of Occurrence*	*Sample of Practitioner Narratives*
Compliance	*10*	*"Some athletes do not like the gym, finding ways to achieve the adaptations can be tricky."* *"Fear factor of certain stimulus' during a week. (E.g., Sprint Exposure and Eccentric Stimulus)."* *"Player buy-in. Sprinting and doing a hard exercise."*
Multi-Disciplinary Team	*10*	*"Some sports coaches lack appreciation and understanding."* *"Coach's/players can ramp sessions inappropriately and result in potential overload at inappropriate times."* *"There are instances where an athlete will have an unplanned team training session. These can vary from 10 competition-based sprints to a 3 mile run and everything in between. These accumulate a much larger workload than anticipated."*

Time with Athletes	*9*	*"Structure of the semi-professional rugby environment, players in full time work with families. Length of training sessions and not impacting on rugby specific training."* *"My key challenge is working for a part time team, which means there are only 2-4 training hours within the week, which is mainly match specific."*
Facilities	*7*	*"No weights at training so players have to perform SL deadlifts at home with whatever equipment they have available."* *"Lack of really good quality assessment (e.g., Nordbord)."*
Volume of Match-Play	*7*	*"Game volume; periodisation around the game schedule."* *"Only work with athletes from Sept-June, they play for teams outside of the school and so there sometimes is an overtraining component, youth athletes who think they are invisible from injury or push return too soon."* *"Crowded fixture schedule makes ability to prescribe maximal strength sessions difficult."*

Athlete Education	*6*	*"The perceived DOMS and people worrying about this occurring and the ramifications of that."* *"The ability of the athlete to understand the importance and completing the exercise correctly."*
Staffing Ratio	*5*	*"Player to coach ratio during some sessions can limit the ability to error identify and correct in technique."* *"Staff to player ratio. Not enough staff to keep track of everything being done properly."*

However, it should be highlighted here that six practitioners stated that they use micro dosing (defined by Cuthbert et al. [2023] as '"the division of total volume within a micro-cycle, across frequent, short duration, repeated bouts") within their training practices to minimise the likelihood of athletes missing session components or increase the compliance with training methods (presumably through reducing risk of adverse effects such as DOMS through lower volumes of training spread across a training week or larger mesocycle). Therefore, it seems that three key areas need to be addressed as a result of the current study. Firstly, practitioners may require better education around the use of micro dosing to improve compliance and reduce potential adverse training effects. Micro dosing of the strength training stimuli is still a relatively new concept within strength and conditioning and injury management, however a recent systematic review and meta-analysis by Cuthbert et al. (2021), offers promising insight into the potential for micro dosing around congested fixture scheduling and indicates a need for more empirical research, to allow practitioners to further develop their understanding and application of the method, however education could be further improved through the availability of continued professional development workshops or clinics offered by governing bodies, but it seems that for future generations of S&C and injury practitioners, academics should develop teaching and learning around the use of micro dosing as a regular practice.

The second key finding from the current study is that athletes require better education in relation to the benefits of training practices and methods used, but also the potential responses to training in terms of long-term adaptations and some of the short-term consequences such as DOMS and whether the presence of DOMS is linked to any decrease in performance levels of increased likelihood of injury. Additionally, educating the athlete as to the strategies used to implement eccentric training, such as the use of micro dosing to minimise individual session exposures, placement of the eccentric training stimulus in the week (e.g., where loading may be positioned away from match-day HSR exposures or incorporated into a warm-up). However, as DOMS is often attributed to unaccustomed exposures to eccentric loading (Mizumura and Taguchi, 2016), a micro dosing approach and / or efforts to ensure a continued compliance to at least some eccentric load across the mesocycle may mitigate some of the likelihood of DOMS in the first place.

While athlete education certainly does not come without its challenges, such as a need to adjust the use of terminology used and buy-in or willingness from the athletes themselves to learn, patient education in a clinical healthcare setting has been shown to be effective. Additionally, as many athletes start their athletic careers in some form of academy, perhaps an early incorporation of athlete education which is continued throughout the athletic journey may develop a long-term understanding of training interventions. Unfortunately, there is a lack of experimental research in relation to the role of athlete education in the subsequent success of training programmes. There is a fairly small amount research in the field of clinical physiotherapy, firstly from that of Lu et al. (2015) that found that the use of a physical training programme combined with the use of educational materials (such as education around the importance of physical exercise in lymphatic health) for the patient reduced the onset lymphedema following breast cancer surgery, compared with just education alone or neither education or physical intervention. While this study does offer some support for the importance of patient education in physiotherapy practice, it is limited by the design of the interventions, given that there was no intervention only group without the educational materials. Additionally, the group sizes were highly skewed with n = 415 in the no control group, n = 672 in the education only group and n = 130 in the education plus intervention group. Two additional qualitative studies were conducted firstly by Mudge et al. (2014) that considered the perceptions of physiotherapists and whether they are comfortable with a 'person-centred approach', and secondly by Jäppinen et al. (2020) that explored physiotherapists perspectives of patient education in total hip arthroplasty. Both studies found that while physiotherapists valued patient education, most felt that their practice was dominated by a biomechanical / biomedical approach to clinical reasoning which limited their capacity to consider the patient at the core of their reasoning.

While the aforementioned studies around patient education in clinical physiotherapy are not directly reflective of S&C practice they likely provide a key social commentary on the practices and perhaps limitations of the applied practitioner, in that are practitioners too heavily focused on evidence-based interventions, rather than adapting to an evidence informed approach that may better suit the individual athlete in front of them, or at least involving the athlete in their evidence-based thinking?

To the candidate's knowledge Weldon et al. (2021) produced the first study that actively considered the perceptions of both coach and athlete in S&C practice and found that athletes clearly considered S&C important or very important for the development of volleyball skill. While there is certainly still a need for more research in this area to investigate the benefits of athlete education in relation to the success of training interventions, it seems wise for practitioners to strive to engage athletes with developing their understanding of S&C practice if it is something they clearly view as important. Developing athlete understanding from some of the basic principles of training at youth level through to some of the more complex rationales such as micro dosing and placement of the training stimuli as athlete's get older, will hopefully help to improve training compliance, and therefore reduce some of the modifiable risk factors for injury.

The third key finding of the current study indicate a need for improved communication forward planning and buy-in across the MDT. While this is by no means an easy task, it seems that issues across the MDT is an issue that potentially restricts applied practices within S&C and sports injury management. The advancements in our understanding of training adaptation, recovery and injury management have increased greatly in recent years, and particularly since the turn of the century with the advancement of technologies and the development of undergraduate programmes in strength and conditioning. As a result, it may be understandable that many non-subject specialists (such as sports coaches) do not buy-in to contemporary athlete management strategies, given that many of the interventions that are supported by contemporary evidence, were not standard practice in previous generations or during the playing careers of many of today's coaching staff. While this may develop in over the coming decades, as new generations of coaches begin their coaching careers being already familiar with more contemporary training and recovery strategies (such as GPS monitoring), there is likely to be yet further advancements and challenges as the sector moves forward. Therefore, while the likes of S&C coaches will continue to face the challenges of educating coaching staff and other members of the MDT as to the importance and rationale of aspects such as load monitoring and periodisation, there seems to be a need for (sport specific) coach education to provide further coverage of the importance of athlete conditioning, load management and recovery.

Table 3-21 Coded responses relating to the open-ended question on areas of applied practice that could be further developed, the frequency count of coded responses and samples of practitioner qualitative narratives.

Compliance Strategy	*Frequency of Occurrence*	*Sample of Practitioner Narratives*
Athlete Testing / Monitoring	*19*	*More accurate tracking and a wider variety of overall testing of performance (acute and chronic),* *"Access to technology to provide more objective feedback on training adaptation - drive buy in."* *"More frequent monitoring of strength and architecture of hamstrings. Too infrequent at the moment - would help with interventions."*

		"HSR currently performed during football session within game training, but we have objective measurement tools available."
Athlete Education	*8*	*"Education to the players, so they understand the reasons why they are doing it, how it's likely to make them feel, and not to worry if they do feel that way."* *"Access to technology to provide more objective feedback on training adaptation - drive buy in."*
Increased Time with Athletes	*6*	*"More frequency of training and greater volume of strength training."*
Developing an Individualised Approach	*6*	*"I could improve by providing all players with hamstring injury prevention programmes, rather than a select few, who have either suffered previous HSI's or have personally asked for a programme."* *"Continue to alter sets/reps/range/distance based on individual responses / beliefs to exercise and training."*
Practitioner Education	*5*	*"More understanding of interactions between gym-based training and sprint performance (acute and chronic)."* *"I'd like to discover methods of training to help prepare athletes for the "chaos" that can happen in their sport. A slight slip, overstretch, etc."*

		"An equivalent hamstrings load metric. It's difficult to add apples (HI load) with oranges (tonnage of lifting). It would be useful to have a metric that it would be inform us that [for instance] 3 x6x30kg of hams curls equals [a similar volume-load] to 45m of high intensity run."
Developments in the MDT	*5*	*"More collaboration between S&C staff and myself, gathering and building around both school and outside schedule to take everything into consideration."* *"Better long-term planning and buy-in from coaches."*
Training Consistency	*4*	*"Trying to have more consistency. But when you have a large period of 2 games a week sometimes recovery is more important."* *"More frequency of training and greater volume of strength training. More consistent sprint training exposure."*
Recovery Time / Strategies	*2*	*"Being able to give players the optimum amount of rest."* *"Nutrition advice, as I feel work and rest recovery is best as it can be. Whether nutrition intake could play a role in contributing injuries."*

One key observation from the current study is that there was no significant difference between the volume of NHEs programmed during the off-season compared with the in-season (when considering both the upper and lower end of NHE repetitions reported by practitioners). It was observed in the systematic review and meta-analysis by Ripley et al. (Ripley et al., 2021) that training interventions that contained eccentrically focused hamstring training were superior to those without an eccentric component, but additionally, that compliance rates of >50.1%, with <3 weeks between sessions had a positive impact on HSI risk reduction. It seems crucial here that practitioners, in the most part do try to ensure an eccentric component to training across the in-season and off-season, and as observed in TABLE 3-19, many practitioners do try to ensure that missed training exposures are programmed elsewhere in a training week, or at least athletes are encouraged to engage with the training exposure in their own time. This seems crucial in ensuring that athletes receive sufficient training exposures throughout a training year to reduce HSI risk.

The observation that practitioners try to promote regular eccentric training exposures throughout the training year may also be crucial given the findings of Timmins et al. (2016) that while 6-weeks of eccentric hamstring training can lead to significant increases in BFLH FL, those positive adaptations can return to close to baseline levels following the removal of the eccentric stimulus for over a period of two weeks.

On the other hand, it could be argued that training compliance, and likely then HSI risk could be reduced further when looking at the volumes of NHEs reported to be programmed by practitioners. The average lower end of weekly NHE repetitions (12.7 ± 12.3 in-season and 17.3 ± 12.2 off-season) and upper-end (45.5 ± 23.4 off-season and 37.5 ± 25.5 in-season) may still be higher than the minimum dose required to achieve positive adaptation. Cuthbert et al. (2019) observed that NHE repetitions of eight per week may be sufficient to induce significant improvements in FL. However, minimum dose requirements for adaptations in maximal strength are still somewhat unclear, as the programmes used in studies such as Presland et al. (2017a) and Siddle et al. (2022) incorporated an initial 2-week period of fairly high volumes (96 NHEs per week) which was only then followed by eight weekly repetitions. Most practitioners in the current study, reported a preference for the use of four sets (FIGURES 3-2 and 3-3) of varying repetitions when programming the NHE, however when considering the observations from those studies included in the systematic review and meta-analysis of Cuthbert et al. (2019) it may be feasible to adopt a smaller number of sets and repetitions than what seems to be applied by the practitioners in the current study (e.g., two sets of four repetitions). However, further research is required to investigate the adaptations in strength and FL from low volume interventions without an initial period of high-volume training. There is also scope for further investigations into the use of micro dosing training exposures, to see whether an exposure of eight weekly repetitions split across a training week may also be sufficient to achieve adaptation, which may allow practitioners to implement eccentric training in time-efficient doses which may be less likely to be associated with DOMS.

It is also evident from the current study that most practitioners utilise NHE-based resistance training alongside other methods of resistance training and HSR, however currently there is a lack of training intervention studies examining the effects of concurrent training methods for the mitigation of HSI risk or HSI incidence. When considering the lower end of non-NHE resistance training volume (FIGURE 3-5), there was no significant difference in volume between the in-season and off-season, however there was a moderate-significant (g = -0.70; p = 0.014) reduction in volume at the upper end (FIGURE 3-6) in-season compared with off-season which is likely due to decreased time with athletes and a need to periodise training around competition. The RDL was the most commonly used non-NHE resistance training exercise, followed by variations on the glute bridge / hip thrust. As exercises that incorporate knee flexion with concurrent hip extension may have the potential to increase training adaptations in the BFLH due to the combined knee flexor and hip extensor torques, (Lee et al., 2018) which are associated with the actions of the BFLH and that are also associated with HSR (Green et al., 2020; Malone et al., 2017). However, there is currently a lack of training intervention studies to investigate the use of such training methods for the mitigation of HSI risk, or to investigate the benefits of more hip-dominant training methods alongside the NHE or HSR training.

3.5 Limitations

There are a number of limitations associated with the current study, which are identified herein, and further addressed in CHAPTER 4 Firstly, when interpreting participant responses, there was a broad range of detail with which participants responded to either to overall survey, or to some particular questions. For instance, some questions (e.g., the open-ended question relating to missed training components, presented in TABLE 3-19), some participants simply responded 'yes' without providing further comment on how they managed missed training elements, this therefore limits the depth of analysis of responses from those six participants.

Additionally, the somewhat chaotic reality of working in applied sport means that there likely is no such thing as a 'typical' training week for many of the practitioners that took part in the study. Therefore, while the way in which the survey was presented does provide a general overview of applied practice and was designed to be user friendly and not overly time-consuming for the participant, many of the questions do not capture the nuances of training around fixture congestion, with groups and individual athletes.

There are some areas in which some additional questions could have provided more depth to the participant's responses. One example of this is that the questions did not push the participants to comment on the placement of HSR sessions in the training week. While some did comment on positioning HSR exposures further away from match exposures, it would have been beneficial to understand if this is a widely adopted practice. Furthermore, there could have been additional scope to consider whether practitioners placed specific emphasis on exposures to maximal or near-maximal acceleration and deceleration efforts, given observations from the likes of Bowen et al. (2020) that non-contact injury risk is increased when athletes have low exposure to deceleration efforts.

Finally, one of the original research questions associated with the current study was 'how do hamstring training practices differ across geographical locations?', based on the early observations that HSIs were potentially decreasing in Australian rules football, but increasing in elite European soccer. Unfortunately, the responses to the survey were skewed towards those based in the United Kingdom, with insufficient representation from southern hemisphere countries to answer that research question.

3.6 Conclusion

Based on the results of the current study, it can be concluded that most practitioners utilise a number of methods to promote athletic development and reduce the risk of HSI, which include regular exposures to HSR, NHEs and other forms of resistance training methods both in-season and off-season. There may be some differences in approaches between the in-season and off-season, particularly with regard to the volume of resistance training programmed being significantly higher off-season compared with in-season. While running-based sessions in the off-season seem to consist of higher-volumes, these sessions do seem to be more focussed on technical coaching cues, and preparation drills as opposed to HSR. One of the themes identified around the coaching focus of off-season running-based sessions was around front side mechanics, however little further elaboration was provided here. Previously, Freeman et al. (2021) surveyed the beliefs and practices of high-performance managers working at the elite level in Australian rules football. It was observed from the responses in the study of Freeman et al. (2021) that all of the nine coaches that responded to the survey implemented coaching with the aim of improving sprinting mechanics, with a theme centred on minimising an over-striding, due to the perception that an over-stride ‘overloads’ the posterior chain. Additionally, the coaches surveyed in the study of Freeman et al. (2021) also indicated that they try to improve lumbo-pelvic control during their sprinting sessions. It has previously been stated by the likes of Schuermans et al. (2017) Chumanov et al. (2011) that ‘abnormal’ pelvic motion can contribute to reduced co-contraction of lower limb musculature, leading to an increase in HSI risk. Therefore, the findings of the current study and that of Freeman et al. (2021) may indicate that applied practitioners value the role of coaching sprinting mechanics for the mitigation of HSI risk, however further empirical studies on the efficacy of sprint running technique modification on the HSI incidence are required.

It is apparent from the results of the current study that, there is disparity between the thresholds used by practitioners to define HSR and sprinting in both absolute and relative terms. This observation is consistent with those from a narrative review by Freeman et al. (2023) that reported disparity between HSR and sprint velocity thresholds across 15 published research papers. Studies included in the narrative review by Freeman et al. (2023) reported absolute HSR velocity thresholds between

3.47 – 5.50 $m \cdot s^{-1}$, (12.49 – 19.80 $km \cdot h^{-1}$) with relative thresholds between 40 – 60 % of maximal velocity and absolute sprint velocity thresholds of 5.55 – 8.33 $m \cdot s^{-1}$ (19.98 - 29.88 $km \cdot h^{-1}$) and relative sprint thresholds between 78 – 83% of maximal velocity. The practitioners in the current study indicated that they use HSR thresholds of 5.50 – 6.00 $m \cdot s^{-1}$ (19.80 – 21.60 $km \cdot h^{-1}$) and sprinting velocities between 7.50 – 8.00 m·s-1 (27.00 – 28.80 $km \cdot h^{-1}$), with relative thresholds between 50 – 75% and > 85% of maximal velocity for HSR and sprinting, respectively. From the observations from the current study, it seems that there is still a disparity between thresholds used to define HSR and sprint velocities in absolute and relative terms across practitioners. Generally, participants in the current study applied higher or equivalent absolute threshold values for HSR than all 15 studies included in the study of Freeman et al. (2023) and higher absolute threshold values for sprinting than all but two of the studies. However, when considering practitioners and researchers that have utilised relative velocity thresholds for HSR and sprinting, it may be questionable whether sufficient intensity can be achieved where HSR velocity thresholds of 50-75% were reported in the current study and as low as 40% by the likes of Clarke et al. (2017) With regards to sprinting sessions using relative velocity thresholds, most of the practitioners surveyed in the current study indicated that they use thresholds of ≥85%, whereas none of the 6 studies included in the narrative review of Freeman et al. (2023) that indicated relative sprint intensities exceeded 83%, with some using thresholds as low as 58%.

While programming running sessions based on relative thresholds may offer a more individualised approach (particularly in sports such as American football where players in certain positions are highly likely to possess different running velocity profiles; such as the defensive line compared with wide receivers), it seems that the disparity between perceptions and use of absolute and relative thresholds may be a contributing factor to practitioners failing to expose their athletes to a sufficient HSR or sprint training stimulus. This can be further supported by a survey study conducted by Freeman et al. (2021) where surveyed high-performance managers working in the AFL indicated that they would consider relative velocities of ≥90% of maximal velocity as sprinting, yet no practitioner indicated that they measure sprinting values in excess of 85% of maximal velocity.

While there may be scope for debate around the most appropriate absolute and relative thresholds for HSR and sprinting, there does seem to be practitioners in the field that are prescribing running sessions that are not likely offering sufficient intensity in comparison to HSR and sprint velocities achieved in competition, such as those prescribing session intensities of 50-70% of maximal velocity. There is also evidence of peer-reviewed literature sources which also used intensities that may be too low to be truly considered HSR or sprinting, which may therefore have a negative impact on applied practice. To illustrate why lower intensity running sessions may be suboptimal in mitigating risk of BFLH strain, the study of Chumanov et al. (2011) can be considered. Chumanov et al. (2011) modelled net hamstring muscle forces and negative work of the hamstrings during the swing phase of incremental velocity running trials, derived from three-dimensional motion capture. From the estimations of Chumanov et al. (2011) it can be noted that as running velocity increases from 80% to 100% of maximal velocity, hamstring muscle force increased significantly from 36 $N \cdot kg^{-1}$ to 52 $N \cdot kg^{-1}$, and negative work increased from 1.6 $J \cdot kg^{-1}$ 2.6 $J \cdot kg^{-1}$. These findings may therefore indicate that where lower velocity running is programmed, the athlete is likely to experience lower muscle forces and total negative work compared with maximal velocities achieved in competition. Therefore, where the practitioner aims to utilise HSR or sprinting as a training modality with the aim of mitigating HSI risk, careful consideration should be given to ensure that appropriate running velocities are achieved relative to the athlete's maximum.

It seems key here that practitioners have an appreciation for regular training exposures and are conscious about trying to implement strategies to minimise missed training elements. It has been reported that training interventions that incorporate eccentric loading strategies <3 weeks apart seem to be more superior than programmes that do not, Ripley et al. (2021) and FL lengthening in response to eccentric loading has been seen to return towards baseline following 2-weeks of stimulus removal (Timmins et al., 2016).

On the other hand, practitioners did identify that time with their athletes and compliance with training programmes are key limiting factors to their current practice. While recommendations from the literature regarding the need for regular training stimuli seem to be well adopted in applied practice, recommendations around minimum dose response to NHEs is perhaps not yet being broadly applied. Most practitioners reported that they are still programming the NHE in excess of the eight weekly repetitions that seem to be sufficient for positive adaptation, which may be a contributing factor to a lack of compliance and the extended periods of time required to implement some of the NHE volumes preferred by practitioners in the current study may be eating into valuable time with athletes that could be spent working on other areas if a lower NHE volume was adopted. While there is certainly still a need for further research into low volume and micro-dosing approaches to resistance training, currently it does seem that if practitioners were to adopt a lower weekly NHE volume, some of the limiting factors to practice could be mitigated.

HSR as a training method seems to be broadly applied in addition to HSR in sport-specific training sessions. While the volumes and frequency of HSR both in-season and off-season seem fairly low, it is clear that practitioners identify that monitoring of HSR across the MDT could be improved, however this comes with associated costs of technologies such as GPS and the time and financial resources required to interpret and plan proactively and reactively around such data. Additionally, it seems that planning of sessions that contain HSR and sprinting could be better coordinated across the MDT, as several practitioners identified that their athletes are often exposed to tactical and technical coaching sessions which consist of HSR drills that have not necessarily been factored into the training plan or may cause unexpected acute spikes in total HSR volume in the training week.

Furthermore, it is clear from the current study that, given the broad application of concurrent training methods in applied practice, there is very much a need for further training intervention studies to demonstrate the benefits of such training approaches to establish effective practice and a minimum dose response. Therefore, it is likely that a stronger link needs to be established between researchers and applied practitioners in order to more closely monitor athlete training and quantify adaptation, given the significant difficulties of recruiting participants for sufficiently powered training intervention studies outside of a sporting setting as well as the questions relating to ecological validity of training intervention studies using non-elite athletic populations being used to inform the training practices of those working in elite sport.

Chapter 4 Practices and Perceptions in Hamstring Training for Injury Prevention and Enhancement of Athletic Performance: A Qualitative Analysis

4.1 – Background

From CHAPTER 3, it is clear to see that the applied practices in relation to training for the mitigation of HSI and enhancement of athletic performance are highly nuanced. While the fixed response and open-ended questions included in the survey from CHAPTER 3 provided some much-needed insight across and number of sports and professions, it seemed that in order to develop a more in-depth qualitative appreciation of these nuances and the underpinning rationale behind the approaches to training adopted by practitioners a further qualitative analysis was warranted through the means of individual practitioner interviews.

Recently a number of survey-based mixed methods analyses have been conducted into various aspects of applied practice in strength and conditioning, practices and perceptions of coaches in soccer, (Loturco et al., 2022; Weldon et al., 2021; Weldon et al., 2022) volleyball, (Weldon et al., 2021b) cricket. (Weldon et al., 2021b) and rhythmic gymnastics (Debien et al., 2022) Furthermore, practices and perceptions of fundamental movement skills in grassroots soccer (Duncan et al., 2022) have been investigated as well as the perceptions of strength and conditioning from the athlete's perspective in soccer (Weldon et al., 2022) and volleyball, (Weldon et al., 2021b) and rhythmic gymnastics (Debien et al., 2022) and the agreement between sports coaches and physical preparation practitioners in load monitoring in soccer. (Weston, 2018)

However, the existing investigations into the practices and perceptions of practitioners in applied sport are limited to survey style data collection methods. While surveys do allow the researcher to adopt a mixed methods approach to study design through fixed response and open-ended questions, the nature of online surveys does not allow for two-way conversation. A lack of conversation does not allow the researcher to ask individualised follow-up questions, which may result in a lack of exploration around the nuances, reasonings and potential individual biases that may underpin applied practices.

From CHAPTER 3, it was clear that practitioners tend to utilise combined training methods that include the use of resistance training and running drills (although the broad range of absolute and relative velocity thresholds to identify HSR and sprinting could be questioned). However, the nuances around how practitioners approach aspects of programme design such as exercise selection, placement of resistance and running sessions around competitive fixtures and how dynamics within the MDT influence applied practice (both negatively and positively).

Additionally, it was identified through CHAPTER 3 that practitioners value athlete education and engagement with training, however the constraints of survey-based data collection likely did not allow for investigation into how practitioners approach athlete education or the methods used to promote athlete engagement and involve the athlete in programming decisions.

4.2 Aims

The aim of the current study was to interview applied practitioners to develop a detailed understanding of the highly nuanced aspects of applied practice in the area of HSI risk mitigation and training for enhanced athletic performance. The semi-structured interviews were designed to engage practitioners in a two-way discussion around the individual challenges they face in their role, their approaches to programming and rationales and biases that underpin such decisions.

4.3 Methods

4.3.1 Participants

Twelve participants volunteered to participate in the study. Eleven of the participants were strength and conditioning coaches with either a master's in strength and conditioning and / or accredited by the NSCA or UKSCA and were based in the United Kingdom. One of the eleven UK-based participants was a chartered physiotherapist in their current role but also held master's qualification in strength and conditioning from an NSCA accredited institution. One participant was a licensed physiotherapist based in Argentina and a member of the Asociación de Kinesiología del Deporte.

Table 4-1 Participant characteristics. Some participants worked with athletes from multiple sports so only the sport which they worked in predominantly is listed as is the level of athlete with whom they predominantly worked.

Participant	Sex	Age	Sport	Athlete Level	Profession	Highest Qualification	Years in Profession
1	Male	25-34	Lacrosse	Professional	S&C Coach	PhD	7-9 years
2	Male	25-34	Soccer	Youth	S&C Coach	MSc	1-3 years
3	Female	25-34	Soccer	Youth	S&C Coach	MSc	4-6 years
4	Male	18-24	Rugby	Youth	S&C Coach	MSc	1-3 years
5	Male	35-40	Soccer	Youth	S&C Coach	PhD	15+
6	Male	35-40	Soccer	Professional	Physiotherapist	MSc	15+
7	Male	25-34	Soccer	Professional	S&C Coach	MSc	7-9 years
8	Male	41-50	Rugby	Youth	S&C Coach	MSc	15+
9	Male	35-40	Soccer	Professional	S&C Coach	MSc	10-15 years
10	Male	35-40	Soccer	Professional	S&C Coach	MSc	10-15 years
11	Male	25-34	Soccer	Professional	S&C Coach	MSc	7-9 years
12	Male	25-34	Rugby	Professional	Physiotherapist	BSc	10-15 years

4.3.2 Data Collection

The study used individual practitioner interviews to investigate practices and perceptions around training for athletic development and mitigation of HSI risk factors. The interviews utilised a semi-structured format, made up of six broad areas for discussion as follows: (1) practitioner profile; (2) job role challenges; (3) resistance training; (4) high-speed running; (5) athlete testing; (6) views of research. These broad areas were split into subthemes of questions to provide some structure to each interview, the natural course of conversation allowed for some deviation from these subthemes as well as individualised follow-up questions based on practitioner responses. The general subthemes have been outlined in TABLE 4-2.

Table 4-2 The 6 broad areas (left) covered under the semi-structured interviews with the general subthemes (right).

Question Area	Subthemes
Practitioner Profile	• Primary job role • Level of athlete you currently work with • Primary sport you currently work in • Experience level
Job Role Challenges	• What are the key challenges in your role when it comes to reducing the number or risk of hamstring strain injuries? • What, as practitioners do you think we could be doing better to reduce the number of hamstring strain injuries? • What is the approach to managing hamstring strain injuries (prevention or rehabilitation) in your organisation? Multidisciplinary approach?
Resistance Training	• What is your approach to strength training with your athletes? • How do you approach volume-load prescription? • What are the barriers to strength training with your athletes? • Do you adjust strength training volume-load or exercise selection in response to fixtures congestion / markers of fatigue?
High-Speed Running	• What are your views on the programming of HSR for your athletes? • Do you specifically programme HSR as a training intervention? • If so, how? • If not, why? • What are the barriers to HSR training with your athletes? • How do you think we should be monitoring exposure to high-speed running and do you think we need to adjust training practices in response to high-speed running volume? • Do you or do you think there is a need to adjust hamstring training around periods of fixture congestion or indications that the athlete may be in a fatigued state/may have experienced a spike in usual training volume/intensity?
Athlete Testing	• Do you use any objective markers of assessing athlete risk of HSI? • If so, what and why? • Do you set any particular goals or use this data to classify injury risk or inform coaching/selection? • Do you use any objective markers of assessing adaptation to training in terms of athletic performance? • If so, what and why? • Do you set any particular goals or use the test results to inform future training? • Have you seen any difference in injury rates or performance as a result of your athlete monitoring?

Views on Research	• Do you feel that the available literature in the field of hamstring strain injury has changed/developed your practice for better/worse? • If so, how? • What areas of literature do you think are lacking and what do you feel should be the direction of future studies? • Do you feel that interventions can actually reduce the number of hamstring strains in sport or are they unavoidable? • What are your thoughts on the widely cited recommendations for hamstring training such as the volume recommendations around the Nordic hamstring exercise? • Why do you think hamstring strain injury rates remain high in many sports?

Semi-structured interviews were carried out in a combination of in-person and online via Microsoft Teams. All interviews were audio recorded to allow for transcription. Interviews were transcribed using Descript AI voice-text transcription (San Francisco, CA, USA). Initial familiarisation with the data involved the researcher listening to the interview alongside the transcript to check for accurate transcription and correct any misinterpretations or inaccuracies.

4.3.3 Data Analysis

Following transcription, the data familiarisation continued by the researcher reading each transcript a minimum of three times. Next, all transcripts were imported into Nvivo 12 Plus software (Lumivero, Denver, CO, USA) to identified initial codes within the data set. During this phase, initial codes were identified from each individual transcript, connecting them to a central theme or concept, and referencing the fundamental segments or elements within the raw data (Boyatzis, 1998), this process was repeated throughout each transcript. Ten initial codes were identified and are presented in TABLE 4-3.

Table 4-3 The ten broad codes identified from the interview transcripts. Each code is presented in the left column with the right column showing the frequency with which each code appeared across all transcripts.

Code	Number of References
Areas for Professional Development of Practice	47
Athlete Testing, Monitoring and Profiling	82
Athlete's Values, Beliefs and Perceptions of Strength and Conditioning	35
Demands of Scheduling	28
Demands of Sporting Competition	19
Injured Athletes	33
Job Role-Specific Challenges	39
Multidisciplinary Team Dynamics	48
Programming of Training	171
Travelling	16

Next, as per Braun and Clarke (2006), the initial codes were reviewed to establish broader themes within the data set with these themes being broken down into ‘main’ themes with some further sub-themes for clarity. Themes were then reviewed, which led to the removal of some sub themes and the sub classifying of some of the broader themes, particularly those pertaining to programming of training, which required further sub classification into programming around resistance training, exercise selection, high-speed running and micro-dosing of the resistance training stimulus. The resulting 5 broad themes and their associated sub-themes are presented as a theme framework in TABLE 4-4.

Table 4-4 The final five broad themes taken forward for analysis in the left column with associated sub-themes presented in the right column.

Theme	Sub-Theme
Areas for Professional Development of Practice	Knowledge & Understanding Feedback to Athletes
Athlete Testing, Monitoring and Profiling	Benchmarking Injury Risk Identification High-Speed Running
Athlete Values	Engagement Education
Job Role Challenges	Demands of Sport Multidisciplinary Team Dynamics
Programming	Exercise Selection Resistance Training High-Speed Running Micro-Dosing

4.4 Results

Theme 1: Areas for Professional Development of Practice

A theme of discussion within the semi-structured interviews centred on coach's knowledge and understanding around two key areas, which related to the implementation of isometric training, which was particularly eminent in those coaches working with youth athletes. On the other hand, those working with elite senior-level athletes discussed how they utilise isometric-focused training heavily within their training programmes. Here it should be noted that, as expected, those working with youth athletes stated that they tend to encounter relatively few HSIs within their athlete groups, so focused more on the potential for isometrics in general strength training as opposed to with a specific focus on injury risk mitigation.

'I've been using more isometrics, but I don't really know enough of why I'm using that type of isometric for that duration with that person. I kind of get the gist of how they work, but I don't really. If someone said to me, why am I doing a maximal contraction for five seconds, I'd be like "um, you know, like, I think it's good" but I don't really understand the difference between contraction durations, long versus short levers, intensities etc. That is definitely something I think I could do better with.'

Practitioners also discussed a desire to develop their use of augmented feedback for athletes, particularly around the use of video recordings to feedback to their athletes and monitor progress.

'One thing I think [that] I could personally be better at is using the video recordings that we take. We record a lot of things like sprints etc. but I don't think we're always great at feeding that back and closing that feedback loop with the players. I'm always challenging myself to keep things fresh and make sure things do not get monotonous.'

Additionally, practitioners working across youth and senior athlete groups also highlighted a desire to continue to develop knowledge and understanding around the potential dose-response relationships of training and how to better individualise training, particularly in larger group settings.

'In terms of future directions, I think getting a dose response relationship potentially for training load. If we're going to use it [dose response monitoring] for both monitoring and performance measurement, we need to know, someone of 'this' ability or 'this' level of strength can give 'this' level of output and have 'this' effect from it. Because when you have got a whole group of 20 players or more, all varying, it gets difficult to look at individuals. So, we'll have, peak game pace which is our worst-case scenario stuff and we see the group average is like 'the squad had reached that peak game pace'. So, we've got the intensity that we wanted but within that there's like your standard deviations, your 95% confidence intervals or whatever, so there's some players who aren't reaching that and some that are going above and beyond'.

There was a clear theme around practitioners implementing contemporary research around the mitigation of HSI risk factors in their practice. However, practitioners also discussed a need to continue to develop their knowledge and understanding around the effects of exercises such as the NHE embedded within a more holistic approach to hamstring-focused training.

> *'One thing that has helped my practice a lot is the literature around NHE doses, if you think of some of the earlier work from the likes of Ekstrand, everyone was pushing fairly high volumes of NHEs because it seemed to be what the evidence suggested. In a way I kind of felt like I went along with it because of that [the evidence-base], even if I didn't really think it was right compared with how I programmed other exercises. More recently, I've really reduced the overall volumes that we use, based on that meta-analysis from Cuthbert and some of the things coming out of the Australian groups, which seems to have helped compliance. …I still think some of the evidence is maybe just skimming the surface though. We seem to be fairly happy that we can get decent strength gains with low-volume NHEs, but we seem to know a lot less about other exercises or the effects of NHE training when it's embedded in a more rounded programme. No one is programming just the Nordic alone, so maybe we need to understand that better, or I need to do a better job of monitoring those adaptations with our players.'*

> *'…There's definitely a research bias towards the NHE. Everyone seemed to jump on it and I do feel like that's been of benefit to the industry, definitely on a personal level. But at the same time, when we look at exercises like the RDL which arguably has more of a functional relevance to mechanism of injury and to HSR in general, but there's hardly anything out there on it. Do we know if it's any better or worse than the Nordic?'*

Theme 2: Athlete Testing, Monitoring and Profiling

Similar to CHAPTER 3, strength testing through the use of the NordBord, using the conventional NHE and variations of the NHE was a clear theme. While the specific thresholds of how athletes are benchmarked differed between participants, the use of thresholds relative to individual body mass was evident.

> *'Our baseline benchmark is 10 newtons per kilo, but that then develops through the age groups so as they progress through the next age groups it goes 10 newtons per kilo, progressing to 11 Newtons per kilo through to 12 Newtons per kilo. But there's part of me that questions how appropriate that is for some players. For example, I've got one player that is 45 kilos, so I really doubt that she is ever getting a score of 10 Newtons per kilo on her NHE, but we'll have to see!'*

> *'We tend to look at between-session changes in strength scores, so between 5-7% variation, we think is pretty good. It's when the changes are higher than that is when I tend to look into it a bit more as opposed to "that player is weak or stronger". But going back to things like those NordBord thresholds, like we have players in our squad that can get 500-600 N, whereas the older research tells us to set that threshold of 337 N and it just shows that it can't be that one size fits all model and that some of those stronger players may still suffer injuries even though they're way above the threshold.'*

With regard to monitoring of HSR and sprint running volumes, there was a theme within the dataset around monitoring the total volumes of HSR across a training week, however it seemed that practitioners were more likely to only intervene with further 'top-up' type training sessions in scenarios where athletes had not achieved a certain level of sprint running, rather than only HSR.

> *'Typically, the lads will get their sprints in during games. If they're playing Wednesday and Saturday, then typically the match-day is their sprint exposure. It can be different based on position, for instance some positions on the pitch may not get exposed to top-end sprinting so*

if we pick that up then we're not adverse to exposing them to a very small dose of probably 1-2 repetitions the day before the game if the turn around between games is particularly short or if they have gone 14 days without sprinting then we will exposure them to those 1-2 reps the day before the game.'

Participants discussed that generally the vast majority of their training sessions and match-play are monitored using GPS, which is used as a live metric to continually provide feedback to athletes on the volume of HSR and sprint running completed a particular session and to notify athletes if a new personal best had been achieved. Additionally, those that use mostly continuous monitoring of HSR and sprint running, used the GPS data to ensure that thresholds for volume monitoring of volumes across running zones (e.g., zone five and zone six running) are up-to-date.

On the other hand, in a similar way that practitioners highlighted some criticisms around the use of strength tests to monitor athletes, there were areas of discussion that centred on potential pitfalls of GPS-based monitoring, particularly around the use of set or arbitrary thresholds for HSR or sprint running.

'I think with the absolute thresholds that we've got; I will take some of their numbers with a pinch of salt because I know how quick some of those players are. So, obviously with measurement error aside, we have a player in our group whose GPS data tells us that we that her max speed is 9 meters per second, which is rapid compared to the rest of the group. So, her sprint distance and her HSR distance compared to the rest of the group is crazy because she covers everything at high speed because the set thresholds, we use are low for her, so she accumulates that across the game. But she is able to cope with it because it's a relatively lower percentage of her max compared to everyone else.'

Theme 3: Athlete Values

Participants also discussed their approaches to providing continued feedback to athletes, involving athletes in the process of exercise selection and individualisation of the training stimuli and ensuring that athletes understand the expectations of the session.

> *'It's [running-based data, such as distances covered, and velocities achieved] fed back to them on a daily basis. They'll have training reports that will be fed back every day. So, what they've done in training, what speeds they reach etc. So today, for example, was classed as our speed day. So, people's top speeds will be fed back on the screen, either in the dressing room or in the gym. We're constantly trying to feedback and close that feedback loop, I think that helps in terms of players understanding why they're doing certain things. So, players today knew before they go out to training that it's our speed day and that they're doing the hamstring conditioning and they know they're going out to train and they're going to sprint, and they know that the training is going to be generally high in that sort of zone 6 running. So then in order to complete that understanding it's important to feed it back, it's almost like showing what they've achieved or potentially what they have not achieved so if a player has not hit the expected speed for instance, they know that they're going to have to do a bit more tomorrow or some additional drills at the end of today's session, so it also helps to highlight that to them.'*

Participants discussed their approach to athlete education in terms of helping athletes to understand why they are doing particular exercises and utilising internal feedback such as how an exercise 'feels'. Participants gave particular focus to helping athletes to understand more complex movement patterns such as the hip hinge, which also tied in with using athlete education to potentially dispel some misunderstandings of exercises such as the RDL.

‘I try to educate them on understanding why they're doing what they're doing. Personally, I find the RDL position, or the hinge position the most complex to teach. Some people get it straight away, but some people can take a long time. So, you have to take quite a long time to educate them on why it's important and, and how they should feel.’

‘One thing I think could be done better could be to better educate the players e.g., rather than just give them a programme, educate them as to why they’re doing the exercises, how it will help them? How is it important? Recently, I had a player that was doing deadlifts, and their understanding was that it was an arm exercise that was going to give them bigger biceps because in his mind he’s picking the bar up with his arms so it’s working the arms. Probably a similar case with the RDL because they are picking it up.’

‘… I’ll also consider my exercise selection in that week [congested cycle or after periods without a resistance training stimulus] e.g., RDLs are usually associated with soreness so, I might stay away from those in the first week. They don’t really complain about feeling sore though, the coaches don’t see soreness as a negative or a problem. Then I’ll try to play it down e.g., if there’s some sore hamstrings, I’ll just play it more like a ‘you’ve been working hard’ and we’ll have a bit of a laugh about it.’

It seemed evident from the data set that applied practitioners do not perceive muscle soreness to be a barrier to resistance training, nor do they encounter issues with their athletes not wanting to engage in training due to concerns of soreness. Furthermore, it was apparent that when muscle soreness does occur it is not considered a barrier to participation in regular training activities by either the athletes or the technical coaching staff within the MDT.

‘We very rarely get push-back from the players about NHEs, or for any of our, what they might consider to be “harder”, exercises really. There’s probably only one player that doesn’t do NHEs because of a previous injury, but out of a squad of about 25 players, that’s pretty good. But rarely do we get any push back and I think that is probably because we are pretty

consistent with them and then plus the volume is so low that there's very rarely any issues with DOMS etc.'

Theme 4: Job Role Challenges

Discussions centred largely on the demands of sport, particularly at the elite level of European football. Practitioners discussed challenges around the intensity of match-play, but primarily identified the demands of frequent congested fixture cycles (defined by Julian et al. [2021] as a minimum of two successive bouts of match-play with an inter-match recovery period of <96 h), which was further compounded by the addition of the 2022 FIFA World Cup in Qatar being played during the regular season (November 20 – December 18, 2022).

> *'We train the players hard and we feel that works well, but I guess the biggest challenge is the fixture congestion. Particularly this season with the World Cup being squeezed in. Finding the balance that around the game schedule is probably the biggest challenge.'*

Additionally, practitioners discussed the challenges around programming around competitive fixtures to ensure that athletes are still provided with focused training stimuli and the strategies they use to adapt their training programmes around fixture cycles.

> *'[barriers to our programme] It's primarily the number of games they're playing that limits the amount of work you can do with them outside of games but, we still see the strength element of our programme to be of high importance, even if it is a fairly small micro-dose of the training stimulus.'*

> *'One barrier with regards to gym sessions is when we have a rearranged game. So usually, they play on a Sunday but occasionally they will rearrange a game for a mid-week, so when they do that I still insist that they still do the gym session. We just position it as far away from the game as possible e.g., if the game is at 6pm we will do the gym session at 2pm. Typically,*

I'll keep the load the same, but I'll reduce the volume, so I'll reduce it to 3 sets of 4. The main reason for that is that if the athlete is 13 years old and they're missing a gym session every couple of weeks then it's probably going to be detrimental to them in the long-term.'

Practitioners identified that a strong working relationship with the wider MDT, and particularly in making programming decisions with the input of the technical coaching staff was essential to effective programming and management of training load. Particular focus was given to a strategic approach to active recovery between competitive fixtures and planning around volumes of total running and HSR with the view to minimising impact on technical and tactical training.

'We did a drill in the last camp where midfielders for example were locked into a certain space so had to play through, which means their load is really low, which is great for recovery when it comes to the game. But because they're locked in, there's compensation from other positions. We have one drill where I made the suggestion to actually limit the distance covered and increase the intensity for the wide midfielders. So, we set up cones that funnelled towards the goal, so they couldn't actually use the corners because one of our technical points around creating chances was to, use cutbacks, so it helped the tactical or the technical information, but also limited the amount of high-speed running that those players were exposed to.'

Finally, practitioners discussed the importance of effective communication with technical coaches in order to develop an understanding of planned technical and tactical training sessions. Practitioners identified where effective MDT meetings allow for a coordinated approach to programming and management to athlete training loads.

'This coaching staff are excellent with their organisation, so we try to plan from a drill-to-drill point of view at least around 4 weeks in advance. Obviously, there may be some alteration of that based on numbers [of players involved in the session] etc. but we're pretty certain of what's coming.'

Finally, those that considered their organisation to have an effective MDT with a collaborative approach to training programming discussed the benefits of discussions around the approaches to tactical and technical training sessions that allows all members of the MDT to develop an understanding of the physical demands of training drills.

> *'We've discussed the fact that, if you do a high-press and you get it right, the loading actually [compared with an unsuccessful press of the ball] reduces because you get the ball back quickly, you stay in the opposition's final third and then you control possession. Whereas if you sit back in a mid-block, you've got a lot more distance to travel due to constantly moving. So actually, people seem to perceive that a high press would be more demanding in terms of training loads because it seems like you're covering more at high speed. But actually, they're covering smaller distances to close the ball down, and then you're back in possession. So, we had that discussion with the technical coaches and they're like, "oh, actually, yeah., that does make sense when you describe it like that." But there's so many times where they'll just sit back in a mid-block because they think they're going to conserve that energy by keeping that compact shape, but it is definitely the fashion now.'*

On the other hand, those that identified that they did not perceive the MDT to work efficiently towards a shared approach to programming or did not engage in open dialect across the MDT, discussed that they felt this to be a barrier to their practice or to the effectiveness of training approaches.

> *'We've had some situations recently where the rehabilitator or physio has gone straight to the football coach, then the football coach came back to me so it went around the houses a bit. So, I just had to get my point across that, now we've done too much [training load]. We actually need to recover and that actually all of our injuries at the time, although we had numerous injuries, they were all contact injuries, so he [rehabilitation / physio] was coming out almost retrospectively thinking "we've got a lot of injuries, let's add some more training",*

training that we class "injury prevention" training, without considering the type of injuries and the mechanisms that have led to those injuries.'

Theme 5: Programming

Participants, particularly those working in soccer identified that their primary focus on exercise progression is based on exercise complexity or movement velocity rather than a specific focus on progression of load.

> *'We use movement as like a real sort of cornerstone of the programme. Really the complexity of the movement is something that will progress, so it might not necessarily be an increase in load. We don't really go chasing loads, it's more than movement driven program so that's either the speed of the movement will change, or the complexity of the movement will change There's a lot of single leg work in the programme so there's multiple ways in which we'll progress a player's programme as opposed to just using loads. So really, we focus a lot more on the coach's eye in terms of where we highlight opportunities to progress.'*

> *'I let them self-select the load, but it is guided by me. I don't encourage any increase in load often, if at all. So, for example, with a RDL, I know in my head, if a kid weighs 50 kgs, then the absolute max load I would allow them to work with would be their body weight and that's just me in my head, it's not really something anyone has ever told, me it is just something I work with as a guide. Realistically, I want them to be lifting 60-70% of their body weight. But I am always chasing technical competency, obviously we do want a bit of load as they will need to build that later in the cycle. They do have to ask me if they are able to increase load. There is other factors which underpin how I decide on the load e.g., we have all of their maturation data/maturity status so that does have an impact on the selection of load. For instance, there are players in the U14s that have reached peak height velocity, that I know could lift way more than they do, but it's not something I encourage. Rather, the encouragement is "have you got the technical competency to move on and try the next exercise?"'*

In addition to discussions around exercise progressions within training programmes, participants also discussed their approaches to exercise selection with the NHE and the RDL and its derivatives being highlighted as a key focus across all participants.

> *'I try to take a bit of a holistic approach around the hamstring conditioning side of things. So, I split that into hip strength, hip speed, knee strength and knee speed. So, the hip strength will be some form of RDL or hip hinge movement and then something like a kettlebell swing for hip speed. Knee strength is typically a Nordic and then a leg drive into a Swiss ball so you're getting rebounds and then obviously sprinting is in there too'*

> *'The hip hinge is an ever present in our program, so we'll have a conditioning day where they will have a hamstring specific preparation session before they go out to training. Hip hinge work is always in that. So, within that sort of hamstring programme, there'll be like a hip dominant movement and a knee dominant movement and then like a resisted functional based movement and an unresisted functional based movement so, they are pretty much the four streams of movement that will be in that sort of session.'*

Practitioners discussed that their approach to HSR training is largely dictated by match-play demands of individual positions and roles. Discussions centred on liaising with the MDT to monitor frequency and volume of HSR and maximal velocity running within match-play and technical training sessions. Some practitioners identified that their programme includes a focused HSR element, but that in cases in which athletes are expected to reach high-speed and / or maximal speed within a match-play situation that further exposure to high-speeds and maximal speeds and not then included in the remainder of the training week. As discussed in 'Theme 2 – Athlete Testing and Monitoring' participants discussed that, typically athletes that have not been involved in match day, have played a limited number of minutes in match day or have not engaged in high speeds or maximal speeds due to their positional demands of unique demands of individual games are typically "topped up" with a relatively low volume of HSR or maximal speed training.

Practitioners were asked how they typically programme sprint-based training sessions outside of congested fixture cycles or during pre-season and general preparation training blocks. Practitioners discussed that they primarily use these sessions to add a competitive and enjoyable element to their conditioning-based training. Discussions centred on the use of races between to promote maximal intent across repetitions, with the practitioner manipulating distances used in order to achieve the desired session volumes.

> *'So, there might be one 10m race, one 20m, one 30 m and then maybe one 40 m and two 50 m races. So, I don't specifically record the volume there, but obviously throughout the session they are wearing GPS, so I do keep track of their high-speed metres, using a threshold set through our GPS. So, obviously, the high-speed running that I do with them gets added into what they do in their main training session. But in my session, ideally, I want to get 2-3 maximal speed efforts, which is why I'll set up those longer 40-50m drills.'*
>
> '*We tend to use a mixture of linear and curved drills to be honest. From my point of view in terms of preparing the players for performance on match-day, very few of their sprint efforts are truly linear, recovery runs and things, say if we get hit on the break after an attacking corner might be more linear, but we're keen to give them exposure to a bit of both [linear and curvelinear running].'*

Practitioners discussed their approaches to programming resistance training around periods of fixture congestion. Practitioners identified a number of approaches that they take to mitigate the risks of accumulative fatigue around a congested fixture cycle, which primarily was identified as the micro-dosing of the resistance training stimulus.

> *'The Nordic part of our strength profile and it's in our training programme as well. We use a low volume of Nordics, that's for but then around a real heavy fixture congestion go more towards the side of isometric work as opposed to the eccentric action of the Nordic.'*
>
> *'I typically use micro doses for our strength work throughout the [training] camp, rather than loading it all in one go, which is another reason that as to like actually doing like one set of*

three Nordics and that way it doesn't really have much of a negative effect in terms of soreness but if we dose it throughout the week they should still get the benefit in terms of adaptation.'

4.5 Discussion

Whilst training strategies to mitigate risks of HSIs have been well investigated in recent years, questions have been raised as to whether evidence-based guidelines for injury risk mitigation are being followed in applied practice (Bahr et al., 2015). More recently, meta-analyses (Cuthbert et al., 2019) have indicated that the volume of exercises such as the NHE required to elicit significant and meaningful increases in eccentric knee flexor strength and bicep femoris fascicle length may be lower than the volumes proposed in earlier studies. However, work such as that of Ripley et al. (2021) have indicated that exercise compliance remains one of the primary factors that underpin the success of such training interventions, but even so that the minimum compliance rate of ≥50.1% is relatively low. However, most experimental studies that have investigated the effects of training interventions for the mitigation of HSI risk have focused on single exercise interventions, which arguably lack in ecological validity given that it is unlikely that strength and conditioning practitioners programme only single exercises for muscle groups such as the hamstrings.

Therefore, the aim of the current study was to further expand on the findings of CHAPTER 3 to the applied practices of strength and conditioning coaches in the mitigation of HSI risk and training with the intention of maximising athletic performance. Additionally, the aim of the current study was to also investigate the underpinning rationale for such approaches as well as the potential challenges and barriers to practice which may influence programming and monitoring decisions in the real world.

The interviews revealed that while practitioners do regularly utilise the NHE in their resistance training programmes, the overall volumes of NHEs tend to be low and largely programmed with the intention of micro-dosing the supramaximal eccentric training stimulus, indicating that lower-volume NHE programmes are utilised in applied sport. Additionally, contrary to claims in the literature that NHEs are not used in applied sport due to perceived association with post-training muscle soreness, practitioners did not identify such perceptions as barriers to compliance, nor did practitioners identify that they experience unwillingness from their athlete groups to engage in NHE training. Such findings seem to provide support to the use of micro-dosing to minimise potential negative effects of supramaximal eccentric training but also as a means of increasing compliance with training. It should also be highlighted that the NHE volumes discussed by participants in the current chapter were lower than what was identified in CHAPTER 3, indicating between-practitioner variability in preferences for training volumes.

On the other hand, practitioners discussed strategies to reduce eccentric loading when athletes may be in periods of fixture congestion and in the day immediately following a competitive fixture when residual muscle fatigue may be present from the game itself. Practitioners discussed the use of isometric training during these periods as a means of providing a resistance training stimulus without the associated eccentric action of an eccentrically biased or traditional resistance training exercises. An interesting observation here was that isometric training seemed to be well utilised across youth and senior level athletes, however those working with youth athletes identified that they felt they would benefit from a more comprehensive understanding of the underpinning mechanisms of isometric training, which may highlight a need for the development of more experimental research or a consensus statement around the use of isometric training in youth athlete populations. Although the likes of Dobbs et al. (2020a) have reported that isometric strength and movement competency develop with skeletal maturity, and Radovanovic et al. (2007) and Dobbs et al. (2020b) have reported positive increases in isometric strength from resistance training and concurrent resistance training with ballistic training programmes, empirical evidence around isometric training as a strength focused intervention in youth populations seems lacking.

A key finding of the current study was that practitioners do programme a range of exercises for the mitigation of HSI risk as well as with the aim of maximising athletic performance. While this finding is hardly surprising, it serves to provide empirical evidence that practitioners do not use single exercise interventions, indicating a lack of ecological validity in the majority of existing evidence in the field of training for the mitigation of HSI risks. To the author's knowledge currently only Ripley et al. (2023) has reported adaptations in eccentric knee flexor strength, bicep femoris fascicle length CMJ, IMTP and sprint running performance in response to concurrent resistance and sprint running training, whereas the likes of Marchiori et al. (2022) Sancese et al. (2023) and Freeman et al. (2019) have made direct comparisons between either sprint running training or resistance training. From the current study it seems that further researcb is needed to continue to develop the evidence-base around ecologically valid concurrent training methods, particularly those that incorporate isotonic, isometric and ballistic training methods alongside sprint running.

Further, all participants in the current study indicated that they considered hip hinge action (primarily through the RDL) to be a key movement pattern within their resistance training programme. Practitioners did acknowledge the challenges associated with the technicalities or movements like the RDL, particularly in coaching the hinge movement in younger athletes. However, the current study indicates that there is a very clear perceptual bias towards the benefits of the RDL as a training intervention, even with a lack of empirical evidence to support its use in comparison to exercises such as the NHE. While exercise selection is largely based on general training principles and understanding of adaptations to training stimuli, it seems from the current study that practitioners have an interest in the development of knowledge around the potential adaptations to hip hinge-based training. Practitioners discussed that they perceive the RDL to have more of a functional relevance to the role of the hamstrings during high-speed running. One of the potential limitations of the NHE is that it is knee flexor dominant, in that the knee extension action during the exercise is determined by the participants' ability to generate knee flexor torques through contraction of the hamstring muscles. There is a requirement during the NHE to generate a hip extensor torque and neutral spine posture, which is created by simultaneous isometric contractions of the gluteal muscles and spinal erectors, although there is likely some contribution from the hamstring muscles due to their biarticular nature. However, the resultant hip extensor torques are likely to be relatively low in comparison to the knee flexor torques which therefore may result in adaptations in strength and muscle architecture being non-uniform across the entire muscle-tendon unit, with potentially larger increases in strength and fascicle length towards to distal muscle-tendon unit. If the NHE does elicit adaptations more so in the distal region than in the proximal, this may limit the benefits of the exercise in mitigating risks of proximal muscle-tendon unit injuries.

As there seems to be a need for further research into the use of hip-hinge focused resistance training on markers of HSI risk and athletic performance, there also seems to be a need for researchers to do so in a way that also promotes ecological validity in terms of incorporating the exercise into a holistic training intervention (incorporative of both resistance training and high-speed running), in a similar manner to that of Ripley et al. (2023) As a result, there may be a need for research that not only incorporates hip-hinge focused resistance training such as the RDL into a holistic training programme, but also provides a direct comparison to adaptations to the same programme with a NHE focus in order to provide practitioners with a direct comparison between hip hinge focused training and knee flexor focused training.

Further to the development of research into the training adaptations to NHE and hip-hinge focussed resistance training alongside HSR training, there is also a need to further develop the knowledge base around exercise selection principles relating to hip-hinge focused training. While the likes of Lee et al. (2018) have previously quantified hip and knee joint torques during the RDL, the exercise technique used in their study allowed for knee flexion angles of 32° which is larger than what has previously been recommended in hip-hinge focused training such as the kinematically similar good morning exercise. (Ross et al. 2023) As a result, the subsequent joint torques were likely underestimated due to shortening of the perpendicular distance between the barbell centre of mass and the centre of mass of the hip and knee joints caused by the excessive knee joint flexion. Therefore, further development of knowledge around joint torques and potentially muscle force contributions would allow practitioners to develop a more robust rationale for the selection of hip-hinge focused resistance training.

All of the practitioners in the current study stated that they are involved in the programming and / or leading of HSR and sprint-running training sessions in their role. While most participants stated that the primary HSR and sprint running demands for their athletes are covered in competitive match day, all practitioners stated that there is still a HSR or sprint running focus in their weekly conditioning sessions. An interesting observation was that practitioners tend to use these sessions firstly as an opportunity to expose their athletes to running efforts at or close to maximal intent, but also that they look to identify opportunities to create a sport-specific context to such running-based sessions. Practitioners discussed that in soccer, relatively few HSR efforts are purely linear in nature, which is supported by the Caldbeck et al. (2019) that reported that approximately 85% of sprinting efforts during soccer match play are non-linear and Fitzpatrick et al. (2019) that observed that mean sprint angle across playing positions was 5° but can be as high as 30° in some instances. Additionally, curvelinear running may also offer additional benefits in terms of mitigating for HSI risk. Given that the majority of HSIs that occur during HSR mechanisms, occur in the BFLH muscle, there may be a rationale here to enhance muscle excitation and potentially force production characteristics during HSR. Filter et al. (2020) compared muscle excitation via sEMG in the BFLH and MH during linear and curvelinear HSR. It was reported that there was significant, albeit small ($p \leq 0.05$; d – 0.43) increases in BFLH excitation in the outside leg during curvelinear HSR compared with linear HSR. The findings of Filter et al. (2020) may indicate that curvelinear HSR may offer a more sport-specific means of HSR training but may also offer additional benefits in terms of increasing muscle excitation specific to the BFLH. Increases in MH muscle excitation in the outside leg during curvelinear HSR were statistically significant but not meaningful in magnitude ($p \leq 0.05$; $d = 0.14$). Further, participants in the current study discussed trying to adopt an individualised approach to monitoring weekly HSR volumes and “topping up” on additional HSR in scenarios in which athletes may not have reached near maximal or maximal speed in game scenarios. When considering the differences in mean sprint running distances covered across playing positions in soccer, it seems sensible to adopt such an individualised approach based on positional demands, it may also be worthwhile for practitioners to consider curvelinear running demands across playing positions. It was observed by Fritzpatrick et al. (2019) that in elite academy level soccer players in the United Kingdom, the centre forward position is associated with the most frequent occurrences of curvelinear running (d = 2.1 – 4.4), with the full-back position engaging in the lowest number of curvelinear running efforts (d = -1.8 – 4.4). Therefore, when considering the use of curvelinear running as a training intervention, practitioners may wish to individualise the frequency of such efforts based on playing position but incorporating some element of curvelinear HSR training may be beneficial in further mitigating risks of HSI.

Researchers have previously compared adaptations in sprint running performance from either resistance training versus sprint training or in concurrent resistance and sprint training, however there are currently no existing studies that have reported adaptations to training interventions that include curvelinear running. The lack of empirical evidence around the use of curvelinear running as a training intervention raises further questions around the lack of ecologically valid research into training for soccer performance, given the largely curvelinear nature or HSR in soccer and given the findings of the current study that indicate that curvelinear running is being utilised in applied practice.

Education was a central theme during discussions on challenges within job roles. The current study highlights that practitioners value athlete education in terms of developing knowledge and understanding of the underpinning rationale of training sessions and elements of training. For instance, practitioners discussed the potential for a lack of understanding as a barrier to compliance with training, such as misconceptions around exercises such as RDLs and conventional deadlifts as 'arm exercises' as opposed to for the purpose of developing hip extensor strength. However, the dynamics of the MDT within the sporting environment seem to be both highly nuanced and likely key drivers of success when it comes to athlete monitoring and training, especially with respect to planning of overall training loads and the adaptation of the training environment in light of things like athlete injury. A key theme through all interviews in which participants identified that they felt that they had an effective MDT dynamic within their workplace was communication between individual facets of the team.

The results of the current study highlight the need for effective communication and a multidisciplinary approach to the programming of physical and technical coaching sessions. For example, one participant stated '*This coaching staff are excellent with their organisation, so we try to plan from a drill-to-drill point of view at least around four weeks in advance. Obviously, there may be some alteration of that based on numbers [of players involved in the session] etc. but we're pretty certain of what's coming.*', but others clearly identified frustrations with a lack of communication from other areas of the MDT as to the planning / details of technical coaching sessions. The results also highlight that there is likely a need for continued development of the athlete's knowledge and understanding of physical preparation. One way this may be achieved, particularly in elite sporting academy settings in which young athletes complete part or all of their secondary and further education within the club setting, may be a focused approach within the physical education curriculum. Further enhancing the physical education curriculum to develop an understanding of the underpinning principles of strength and conditioning may help young athletes to enhance their appreciation of the benefits of strength and conditioning for athletic performance and long-term athlete development which may in-turn increase compliance with S&C in the applied setting.

4.6 Conclusion

The current study further expands on the practices and perceptions around training for the mitigation of HSI risk and development of athletic potential that were established from CHAPTER 3. From the current study, it can be concluded that while individual practices are highly nuanced, there is clear themes across practitioners pertaining to the use of concurrent resistance and HSR training which are more varied in nature than the majority of existing literature in the field. These findings highlight a need for the further development of more ecologically valid training intervention programmes. The NHE remains a common theme across resistance training programmes, with practitioners seeming to adopt varying approaches to the micro-dosing of this resistance training stimuli, which was not captured through the more qualitative approach to investigating typical NHE repetition dosages in CHAPTER 3. It seems that practitioners engage well with the contemporary scientific literature from the likes of Cuthbert et al. (2019) and Ripley et al. (2021) in terms of adopting a relatively low repetition dosage and doing so in a way that promotes compliance with the training within their athlete groups. However, practitioners discussed that the majority of the existing literature is heavily focused around the NHE alone and is lacking in empirical evidence around adaptations to hip-hinge focused training and training adaptations to HSR. Therefore, future research should focus on the continued development of ecologically valid concurrent training programmes that include both resistance training and HSR. Currently only Ripley et al. (2023) has established adaptations to training following resistance training with the addition of either the NHE or HSR training. Future researchers could consider investigating adaptations to training from ecologically valid resistance training programmes that include the likes of the NHE and RDL, given their prevalence in applied practice, alongside HSR training.

Chapter 5 Within Session Reliability of Methods to Normalise Electromyography Amplitudes of the Gluteal and Hamstring Muscles.

5.1 Chapter Overview

It was identified in CHAPTERS 3 and 4 that there is a need to further develop the exercise selection rationale and understanding of potential adaptations to exercise interventions that utilise the hip-hinge. CHAPTER 6 presents a biomechanical comparison between the RDL and good morning exercises. One method of exercise comparison that is used in CHAPTER 6 is electromyography. The current chapter outlines a lack of consensus relating to amplitude normalisation methods used in exercise comparison studies and aims to establish a methodological basis on which to select the amplitude normalisation method utilised in CHAPTER 6. The chapter explains the rationale for the normalisation methods selected for reliability and variability analysis. The results of pilot testing which was conducted to compare and evaluate [1] the reliability of three distinct methods of executing an MVIC to obtain an amplitude value to represent 'maximal muscle excitation' from the MH, BFLH and gluteus maximus (GMax) and [2] the variability of the EMG amplitude obtained through such MVIC methods. These methods are then discussed in detail to inform the EMG normalisation methods included for the exercise comparison studies presented later in the thesis.

5.2 Introduction

EMG is a means of estimating the sum of motor unit action potentials which occur at the location of a specific electrode placement during a given contraction. Surface electromyography (sEMG) is a specific branch of EMG which is seen to be convenient and non-invasive and is therefore utilised widely in research and applied practice.

However, sEMG has a number of associated limitations and criticisms which will be discussed herein. Further, recommendations will be made centred on minimising said limitations to promote more reliable use of sEMG technology and inferences made using sEMG data.

When collecting EMG data, the researcher should pay specific attention to the amplitude modulation as any reported amplitudes should be directly related to level of excitation in the area of electrode placement. Failing to minimise risks of data being influenced by factors other than muscle excitation will increase the risks of erroneous conclusions being drawn from the data set. Data obtained through sEMG may in influenced by a number of factors, including but not limited to; electrode placement (Jensen et al. 1993) in relation to nerve innervation and tendons (De Luca et al., 2010), cross-talk from other tissues in the area; perspiration (Winkel and Jørgensen, 1991); skin temperature (Winkel and Jørgensen, 1991); cross-talk from other electrical devices in close proximity; muscle fatigue (Hansson et al., 1992); subcutaneous adipose tissue (De Luca et al., 2010; McGill, 1991); skin impedance (Hewson et al., 2003); and movement artefact (De Luca et al., 2010).

The use of modern wireless sEMG systems greatly reduces artefacts that were previously problematic, such as power line and cable motion artefact noise associated with older, wired sEMG systems and thermal noise originating from the electronics of amplification systems.

5.2.1 – Normalisation of Electromyography

It is recommended that, where researchers wish to make comparisons of EMG data between muscles or muscle groups, between trials, between individuals, or in scenarios which involve the reapplication of electrodes, raw data should be normalised (Burden, 2010). There have been several normalisation techniques reported in the literature (see Table 5-1), however normalisation is usually achieved by dividing the EMG data obtained through a given task by a reference contraction by the same muscle or muscle group (for example a maximal voluntary isometric contraction) (Burden, 2010). Normalising EMG data can then allow the researcher to express data obtained during a given task, as a percentage of the reference value, such as a percentage of MVIC. Reporting normalised EMG data is generally more desirable as it provides a more relatable point of reference, rather than reporting of data in raw microvolts (μV) (Burden, 2010). In addition, normalisation using maximal voluntary contraction has been recommended within the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) (Hermens, 1999) guidelines and is advised in the Journal of Electromyography and Kinesiology author guidelines. Despite normalisation of EMG as common practice and reporting of normalisation methods generally stated as a requirement for authors during manuscript submission; there is no clear consensus on the most reliable method, and little guidance to assist researchers in selection of an appropriate technique.

Lehman and McGill (1999) highlighted the importance of normalising EMG, giving particular focus to the risks of misinterpretation of findings if appropriate normalisation is not conducted. A key criticism of the use of maximal voluntary contractions as a method of normalisation, is that several studies have reported EMG task data >100% of the maximal voluntary contraction. For instance, Contreras et al. (2015) reported upper gluteus maximus, lower gluteus maximus and vastus lateralis EMG amplitudes of 171.75% (± 90.99%), 215.85% (± 83.76%) and 215.83% (± 193.89%) of MVIC during the barbell hip thrust (BHT) at loads of 10 RM. This seems to indicate that the use of an MVIC may not truly represent the individual's muscle activation capacity during a given task (Burden, 2010).

The mode of MVIC used by Contreras et al. (2015) was not entirely clear as it was stated that two methods of MVIC were used and each individual's exercise amplitude was normalised to the MVIC method that elicited the highest amplitude, meaning that it is possible that not all participants were normalised to the same mode of MVIC. One of the MVIC methods used was a prone lying hip extension against a researcher provided resistance as by Boren et al. (2011). The other method of MVIC was a standing gluteal squeeze, in which participants were instructed to externally rotate the thigh by 'screwing the leg into the floor' and then voluntarily contract the gluteal muscles with maximum effort. The researchers did not report any data in support of the use of this method and only stated that it had elicited higher amplitudes in most participants in unpublished data from their own laboratory. While a time-efficient method of EMG normalisation that requires no external input from the researcher is appealing from a logistical perspective, reliability of such a method is yet to be established. Further, if such a time-efficient method of MVIC is viable in the gluteal muscles, it would be advantageous to establish if such methods could also be applied to other muscle groups such as the hamstrings.

As several normalisation methods have been proposed with varying degrees of reliability, there is a need for researchers to consider the appropriateness of normalisation methods to provide a reference for their chosen task(s). The reliability and underpinning rationale of the normalisation methods currently reported within the literature will be analysed herein.

Table 5-1 Normalisation methods reported in the literature, method descriptors and example studies. Table adapted from (Burden, Adrian, 2010).

Normalisation Method	Descriptor	Example Study
$Mean_{Task}$	The average amplitude obtained through performance of a task. Often obtained across a number of trials	Burden and Bartlett (1999)
$Peak_{Task}$	The highest EMG obtained during a task, may be obtained across a number of trials	Bolgla and Uhl (2007)
Submaximal isometric voluntary contraction	The highest EMG obtained through an isometric contraction at submaximal intensity	Bussey et al. (2017)
Submaximal dynamic voluntary contraction	The highest EMG obtained from a submaximal contraction in a non-isometric contraction mode (e.g. concentric or eccentric)	Nishijima et al. (2010)
Arbitrary angle isometric voluntary contraction	The highest EMG obtained from an isometric contraction at an arbitrary joint angle	Bussey et al. (2017)
Angle specific maximal isomeric voluntary contraction	The highest EMG obtained through a maximal isometric contraction at the same joint angle as the task in question	Knudson and Johnson (1993)
Angle specific maximal dynamic voluntary contraction	The highest EMG obtained through a maximal non-isometric voluntary contraction with the same muscle action, and joint angle of muscle length as the task EMG	Rouffet and Hautier (2008)
Angle and angular velocity specific maximal isokinetic voluntary contraction	The highest EMG obtained from a maximal effort isokinetic voluntary contraction with the same joint angle/muscle length, angular velocity or change in muscle length as the task in question	Kellis and Baltzopoulos (1996)
Maximal voluntary squeeze	The highest EMG obtained when asking the participants to 'squeeze' or 'tense' the target muscle	Contreras et al. (2015)
Isokinetic non-angular velocity specific.	The highest EMG obtained during an isokinetic contraction at an angular velocity not specific to the task.	Dalahunt et al. (2016)

It is difficult for researchers to draw comparisons between studies which have applied different normalisation methods. For instance, there are several studies (Allison et al., 1993; Benoit et al., 2003; Burden et al., 2003; Burden et al., 1999; Morris et al., 1998; Shiavi et al., 1987; Shiavi et al., 1986) which have reported greater magnitudes of EMG output when normalising using the $Mean_{Task}$ method, compared with the $Peak_{Task}$ method, based on the normalisation procedure involving dividing the EMG obtained during the trials in question by a smaller denominator (the mean amplitude obtained during the trials).

Some studies such as that of McAllister (McAllister et al., 2014) have not utilised any normalisation of EMG to a reference value, opting only to report root mean square (RMS) values. This makes it particularly difficult to compare findings to those reported in similar studies, or for the data to be utilised as a comparator by practitioners. EMG data and therefore root mean square (RMS) derived from raw EMG varies greatly between participants, and between session when electrodes are removed and reapplied and between-testing sessions (Sousa and Tavares, 2012). Given that EMG data should not be used to track changes in muscle activity over a period of time and rather to analyse acute changes or relative contributions for muscles, it is ill-advised to report data as raw EMG or RMS and opt for reporting to a reference value instead.

Clearly, the research from the likes of Contreras et al. (2015) highlights that the MVIC methods utilised in the published literature are not always truly representative of maximum force generating capacity or potentially not representative of maximum effort, and little empirical data exists to determine associations between MVIC method and force output to establish if methods truly are representative of a muscle's maximum force generating capacity. Furthermore, numerous studies have failed to clearly justify their choice of MVIC or report the reliability of either their normalisation methods or exercise-specific amplitudes. Therefore, there is a need to better establish MVIC methods that are [1] meet acceptable standards of reliability and absolute variability and [2] are representable or comparable to maximal effort contractions.

5.3 Aims and Hypotheses

The aims of the study were to 1) establish within-session reliability and variability of three methods of MVIC that have been previously utilised in the literature for the normalisation of EMG data, 2) provide a comparison of a novel method of hamstring MVIC (hamstring squeeze) that has not yet been reported in the literature, to other previously reported methods of performing an MVIC and 3) to assess the relationship between peak EMG amplitudes during an MVIC performed on an isokinetic dynamometer with isometric peak force data.

It was hypothesised that the 1) there would be no significant difference in peak EMG amplitude between Isokinetic and manual resistance methods, however the voluntary contraction (‘squeeze’) methods for the gluteal and hamstring muscles methods would produce significantly lower peak amplitudes than all other methods. 2) With regards to reliability and variability, it was hypothesised that the MVIC methods that required the participant to apply force against an external load would achieve acceptable levels of reliability and variability in-line with previously published literature, however it was hypothesised that the *‘squeeze’* methods would not achieve acceptable levels. 3) In relation to correlations between EMG amplitude and peak torque, it was hypothesised that that there would be a poor correlation between peak EMG amplitude and peak torque values derived from the isometric knee flexion and hip extension tasks.

5.4 Methods

5.4.1 Participants

Ten healthy collegiate athletes (age: 23.1 ± 3.5 years; height: 176.4 ± 6.6 cm; mass: 79.1 ± 12.8 kg; 4 female; 6 male) volunteered to participate in study 1. All participants identified as resistance trained, taking part in a minimum of two resistance training sessions per week. Exclusion criteria for study 1 included: history of hamstring strain injury, skin condition which prevented the application of electrodes to the skin, or any medical condition which would contraindicate maximal isometric contractions, such as hypertension.

Prior to participant recruitment, the study received ethical approval from the University of Salford Research, Enterprise and Engagement Ethical Approval Panel (application approval reference: HSR1718-108), ensuring that the research adhered to the Declaration of Helsinki for human research. All perspective volunteers received a full participant information letter, covering the aims and rationale of the study, full details of the study protocol and were provided with an opportunity to ask questions of the researcher prior to agreeing to take part. Upon receiving the participant information letter, all perspective volunteers were allowed a minimum of 24 hours to consider their position before making their decision as to whether they would like to take part. All volunteers that wished to take part provided written informed consent and were required to complete a Physical Activity Readiness Questionnaire (PAR-Q), to identify any potential issues that may cause risk to the volunteers if they were to take part.

A priori power analysis, using G*Power (version 3.1, University of Dusseldorf, Germany), determined that a minimum sample of 15 was required for the current study, based on an effect size of 1.0, a power analysis of 0.8 and an alpha of 0.05. Results from both right and lefts legs were pooled to provide a sample of n = 20. It was therefore concluded that the results of the study achieved sufficient power for analysis.

5.4.2 Research Design

The study employed the use of a cross-sectional study design with multiple observations of EMG and isometric peak force. Participants were required to attend the tasting laboratory on one single occasion. Upon arrival to the testing laboratory, all participants received a recap of test procedures and were provided with submaximal familiarisation trials on the IKD to minimise learning effect during testing. Following familiarisation, all participants had their body mass and height recorded. Upon completion of the anthropometric measures, preparation of sEMG electrode placement could commence.

5.4.3 Data Collection

Surface EMG activity of the BFLH, MH and GMax was measured for all trials. Prior to application of sEMG electrodes, standard skin preparation procedures were followed including shaving and cleaning with a single alcohol wipe. Skin preparation has been recommended to reduce impedance between the electrode-skin interface.

Electrode placement involved participants in a prone position on a plinth. BFLH application involved passive flexion of the participants knee to 90˚. A measurement was made between the ischial tuberosity and lateral tibial condyle. The electrode was placed at 50% of the distance between the two landmarks along the presumed orientation of muscle fibres. MH electrode placement was made with the knee remaining in 90˚ of passive flexion. The electrode was placed at 50% of the distance between the ischial tuberosity and medial tibial condyle, in the direction of the presumed orientation of the muscle fibres. *GMax* electrode application involved the participant in a prone position with the hip in 0˚ of extension. The electrode was placed at 50% of the measured distance between the greater trochanter and sacrum, in the presumed direction of the muscle fibres. To check electrode placement, participants were asked to rotate the tibia laterally and medially to visually inspect amplitudes of the BFLH and MH respectively. Lateral and medial rotation of the tibia allowed the researcher to visually ensure that there was minimal cross-talk between the two muscles given their relative close proximity, and extend the hip to visually assess the amplitude of the GM.

Adhesive Ag-AgCl electrodes with a diameter of 10 mm (Noraxon Dual EMG electrode, Noraxon USA Inc, Scottsdale AZ, USA) were used across all trials. Each electrode was attached to a wireless EMG sensor, with a mass of ≤14 g (2B EMG Sensor, Noraxon USA Inc, Scottsdale AZ, USA) via electrode leads, the sensor was adhered to the skin, away from the electrode using double-sided adhesive tape. All EMG data was sent from the sensor to a desktop receiver (Desktop DTS Receiver, Norazon USA Inc, Scottsdale AZ, USA) which was connected to a laptop computer. All EMG data was collected at a sample frequency of 1500 Hz.

5.4.4 Protocol

Three main methods of MVIC were used for this study. These comprised of an MVIC performed on an Isokinetic Dynamometer (IKD) (Biodex Medical System 2, Shirley, New York); a manual muscle test with external resistance applied by the researcher and a standing squeeze test. Each of these three methods was divided into subsections for the hamstrings and gluteus maximus respectively. These subsections were made up of knee flexion (IKD KNEE) and hip extension (IKD HIP) on the IKD; knee flexion with manual resistance applied at the distal, posterior shank (MAN KNEE) and hip extension with manual resistance applied at the posterior distal thigh (MAN HIP); and a standing hamstring squeeze (HS) and standing gluteal squeeze (GS). Participants completed three maximal efforts of 8 seconds for each trial with a 30 second rest between efforts. All trials were complete on both right and left limbs and were performed in a randomised order. Prior to testing, all participants were allowed to complete familiarisation efforts. The researcher visually inspected the EMG amplitudes during familiarisation to ensure activation of relevant muscles.

IKD KNEE

The IKD KNEE procedure involved the participant in prone with the hip in 0˚ of extension and 55˚ of knee flexion. The fulcrum of the IKD was aligned with the lateral epicondyle of the femur and the pad of the dynamometer arm was positioned slightly superior to the malleoli of the ankle and secured in position with an adjustable Velcro strap. Participants were instructed to 'pull' their lower-limb towards to their gluteal muscles with maximal effort. Verbal encouragement was provided from the researcher throughout.

IKD HIP

The IKD HIP procedure involved the participant in prone with the hip in 0˚ of extension and the knee inf 90˚ of flexion. The fulcrum of the dynamometer was aligned with the greater trochanter of the femur and the pad of the dynamometer arm was positioned slightly superior to the knee joint. Participants were instructed to 'push' their leg up towards the ceiling with maximal effort and were provided with verbal encouragement throughout.

MAN KNEE and *MAN HIP*

The MAN KNEE and MAN HIP procedures involved the same participant positioning as the IKD KNEE and IKD HIP procedures respectively, with the researcher applying a manual resistance to the posterior shank, slightly superior to the malleoli for the MAN KNEE procedure and the manual resistance applied to the posterior thigh, just superior to the knee joint for the MAN HIP procedure. Instructions were provided in the same manner as the IKD testing procedures, with participants being instructed to 'pull' the lower limb towards the gluteal muscles and 'push' the leg towards the ceiling, with maximal effort for the MAN KNEE and MAN HIP procedures respectively. Verbal encouragement was provided throughout.

Hamstring Squeeze and Gluteal Squeeze

The HS procedure involved the participant in a standing position with the knees in slight flexion (≤20˚), participants were instructed to manually contact the hamstring muscles with maximal effort. The GS procedure involved the participant in a standing position with the hip and knee in 0˚ of extension. Participants were asked to externally rotate the thigh in a closed kinetic chain position, as if to 'screw the leg into the floor' and contract the gluteal muscles with maximal effort. Verbal encouragement was provided throughout.

5.4.5 Signal Processing

Raw EMG signals were first high- and low-pass filtered (10 Hz and 1000 Hz) (Desktop DTS Receiver, Noraxon USA Inc, Scottsdale AZ, USA). Initial signal filtering was necessary to reduce artefacts in the data such as those associated with movement of cables and cardiac signal amplitudes. The EMG signal was then exported to a custom Excel spreadsheet for further processing and analysis. A RMS procedure was then applied to raw EMG using a 200 m/s moving average window. From the RMS data, peak and mean EMG across each trial were calculated. Mean and standard deviation (SD) across all three trials were then calculated for peak and mean amplitudes.

Raw isometric force data was collected during the IKD trials using a Biodex isokinetic dynamometer (100 Hz, Biodex Medical System 2, Shirley, New York). Force data was not normalised to body mass, given that it was to be correlated with the processed and filtered EMG data, which is not influenced by body mass. Therefore, to normalise to body mass may lead to erroneous inferences being made on any relationships between the two variables. All IKD data was exported for analysis in Microsoft Excel. Peak isometric force was recorded for each trial to allow for analysis of variance and calculation of ICC.

5.4.6 Statistical Analyses

Means and SDs were calculated for each method of EMG normalisation and isometric peak force. Within-session reliability was assessed using the intraclass correlation coefficient (ICC 2,1) and associated 95% confidence intervals (CI) with values of <0.5, between 0.5 and 0.75, between 0.75 and 0.9 and >0.9 were considered poor, moderate, good and excellent, respectively, based on the lower bound CI (Koo & Li, 2016). Absolute variability was calculated using CV%, with ≤12% considered acceptable (Albertus-Kajee et al., 2010). One-way repeated measures analysis of variance with Bonferroni post-hoc analyses, were completed to determine differences between tests. Cohen's *d* effect sizes were calculated for differences between peak EMG amplitudes and were interpreted on the following scale; trivial 0–0.19; small 0.2–0.59; moderate 0.6–1.19; large 1.2–1.99; very large ≥2.00.

Isometric peak torque data was correlated with the processed and filtered EMG data. Peak torque data from obtained via isometric knee flexion was correlated with EMG from the BFLH and MH; isometric torque data obtained during isometric hip extension was correlated with the BF_{LH}, MH and GMax. Correlations were explored using the Pearson product moment coefficient of correlation (*r*). Magnitudes of correlation were established using the following scale: trivial <0.1 small 0.1-0.29; moderate 0.3-0.49; large 0.5-0.69; very large 0.7-0.89; nearly perfect 0.9-1.0.

5.5 Results

Table 5-2 Peak (SD) EMG across all three trials of each test condition; coefficient of variation (CV,%); intraclass correlation coefficient (ICC) with uncertainty of estimates expressed as 95% confidence intervals (CIs).

	Bicep Femoris				
Test	HS	IKD HIP	IKD KNEE	MAN HIP	MAN KNEE
Peak (SD) EMG (mv)	144 (61)	349 (147)	326 (132)	332 (127)	349 (142)
CV (%)	21.9	9.7	11.6	8.9	9.1
ICC 95% CI	.251-.907	.939-.989	.934-.988	.932-.990	.953-.993
	Medial Hamstring				
Test	HS	IKD HIP	IKD KNEE	MAN HIP	MAN KNEE
Peak (SD) EMG (mv)	183 (67)	322 (106)	346 (96)	295 (87)	328 (82)
CV (%)	11.3	13.2	11.11	10.6	9.2
ICC 95% CI	.932-.990	.903-.981	.791-.964	.866-.981	.789-.974
	Gluteus Maximus				
Test	GS	IKD Hip	MAN HIP		
Peak (SD) EMG (mv)	121 (83)	177 (135)	142 (125)		
CV (%)	16.5	9.8	16.9		
ICC 95% CI	.650-.972	.957-.992	.890-.987		

The results of the current study indicate that the MAN HIP and MAN KNEE methods of normalisation produce good-excellent levels of within-session reliability and acceptable absolute variability for the hamstring muscles, The IKD HIP method produced excellent levels of within-session reliability and acceptable absolute variability for the gluteal muscles (TABLE 5-2), the MAN HIP method produced excellent within-session reliability, but absolute variability exceeded acceptable levels.

The HS method produced poor-excellent and unacceptable levels of reliability and absolute variability in the BF_{LH}, respectively, but excellent and acceptable levels of reliability and variability in the MH. The GS method produced moderate and unacceptable levels of reliability and absolute variability for the gluteal muscles.

There was no significant difference in EMG amplitude between any of the MAN and IKD methods for the hamstring muscles ($p \geq 0.05$; d = 0.05 - 0.28). The HS method produced significantly lower hamstring EMG peak amplitude than any of the other methods used ($p \leq 0.05$; d = 0.72 - 1.0). There was no significant difference across any of the EMG amplitudes for the gluteal muscles ($p \geq 0.05$; d = 0.1 – 0.25).

Table 5-3 Peak (SD) isometric peak force across all three trials of both IKD test conditions; coefficient of variation (CV,%); intraclass correlation coefficient (ICC) with uncertainty of estimates expressed as 95% confidence intervals (CIs).

	Hip Extension	Knee Flexion
Mean (Nm)	91	63
(SD)	(32)	(18)
CV (%)	32	29
ICC 95% CI	(.985-.998)	(.811-.965)

Isometric peak torque produced good-excellent between trial reliability ranges for both knee flexion and hip extension, however the coefficient of variance exceeded acceptable levels in both measures (TABLE 5-3).

*Table 5-4 Pearson's r correlations between peak EMG and isometric peak torque for knee flexion and hip extension. ** denotes significant correlation at alpha ≤.05.*

	Isometric Knee Flexion Peak Torque	Isometric Hip Extension Peak Torque
BF_{LH} Peak EMG Pearson's *r* *(alpha)*	.037 (.788)	.028 (.851)
MH Peak EMG Pearson's *r* (*alpha*)	.165 (.233)	.324 (.025) **
GMax Peak EMG Pearson's *r* *(alpha)*	-	.109 (.460)

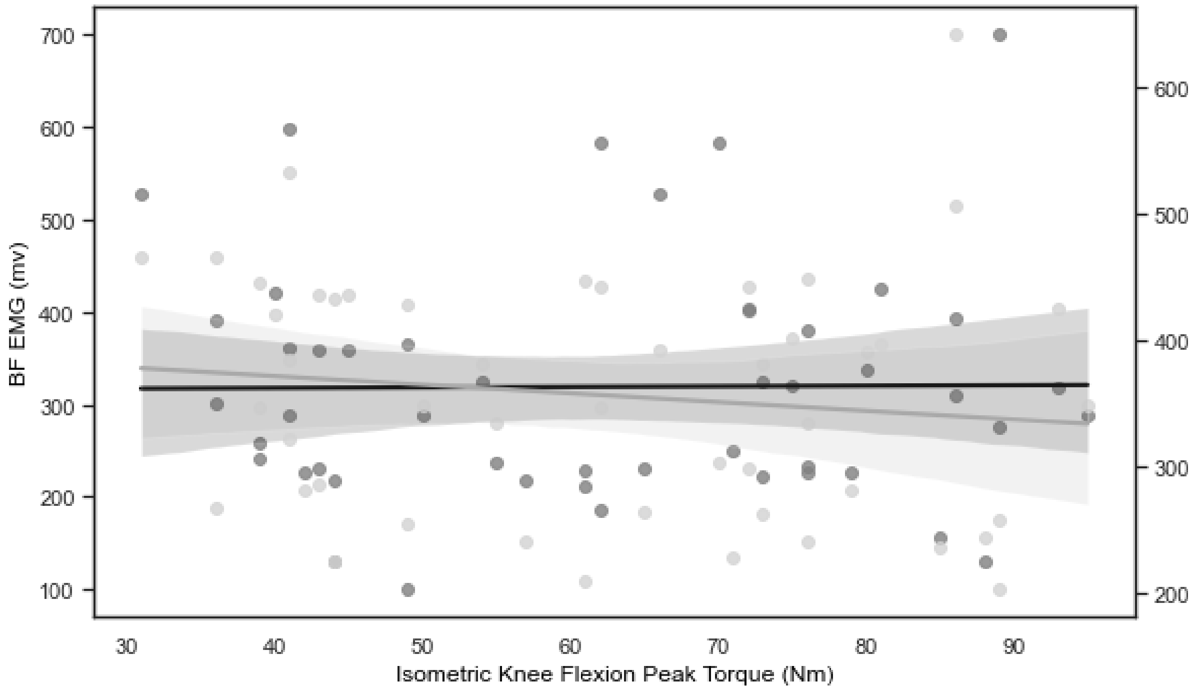


Figure 5-1 Associations between BF (dark grey) and MH (light grey) peak EMG amplitudes (µV) against isometric peak torque (Nm) during knee flexion. Magnitude of correlation is represented by the solid lines with 95% confidence intervals represented by the shaded areas.

There was no meaningful or significant correlation between peak BFLH amplitude and peak isometric knee flexor torque (*r* = *0*.037, *p* = *0*.788) or between peak MH amplitude and peak isometric knee flexor torque (*r* = *0.*165, *p* = 0.233). Scatterplots to represent correlation between hamstring EMG and peak isometric knee flexor torque are shown in FIGURE 5-1, with statistical outputs presented in TABLE 5-4

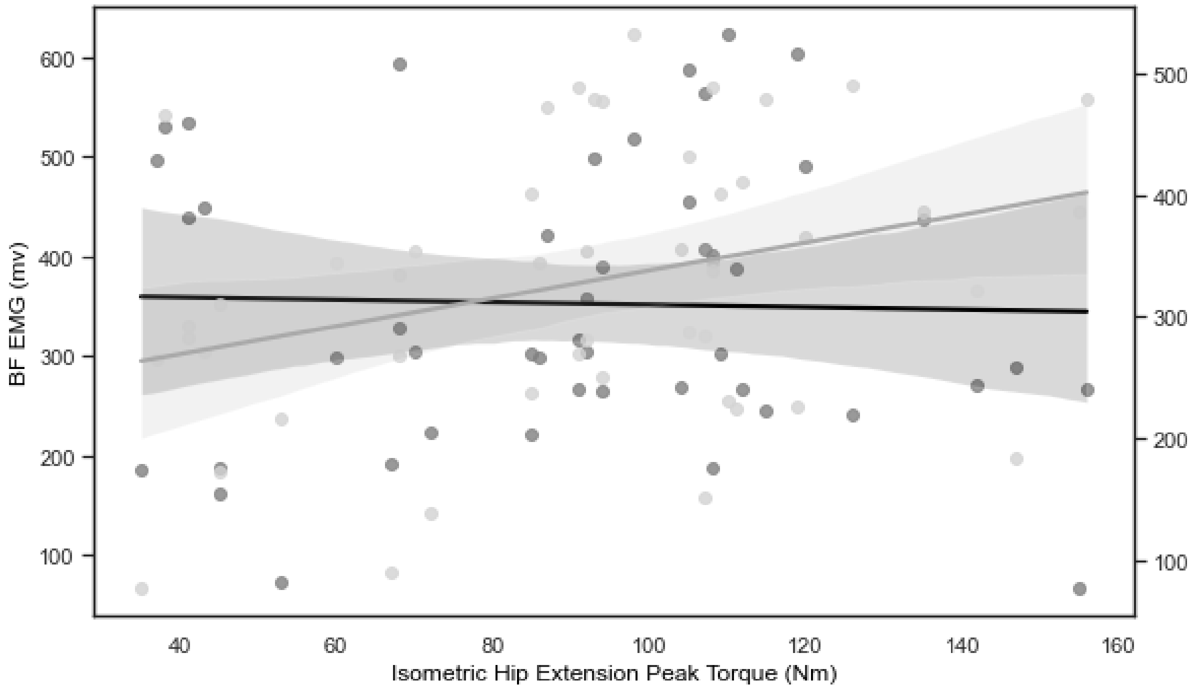


Figure 5-2 A scatterplot of the correlation between BF (dark grey) and MH (light grey) peak EMG amplitudes (µV) against isometric peak torque (Nm) during hip extension. Magnitude of correlation is represented by the solid lines with 95% confidence intervals represented by the shaded areas.

There was a trivial non-significant correlation between peak BFLH EMG amplitude and peak isometric hip extensor torque (*r* = *0*.028, *p* = *0.*851). However, there was a moderate and significant (*r* = 0.324, *p* = *0.*025) correlation between peak MH EMG amplitude and peak isometric hip extensor torque. Scatterplots to represent correlation between hamstring EMG amplitudes and peak isometric hip extensor torque are presented in FIGURE 5-2 with statistical outputs presented in TABLE 5-4.

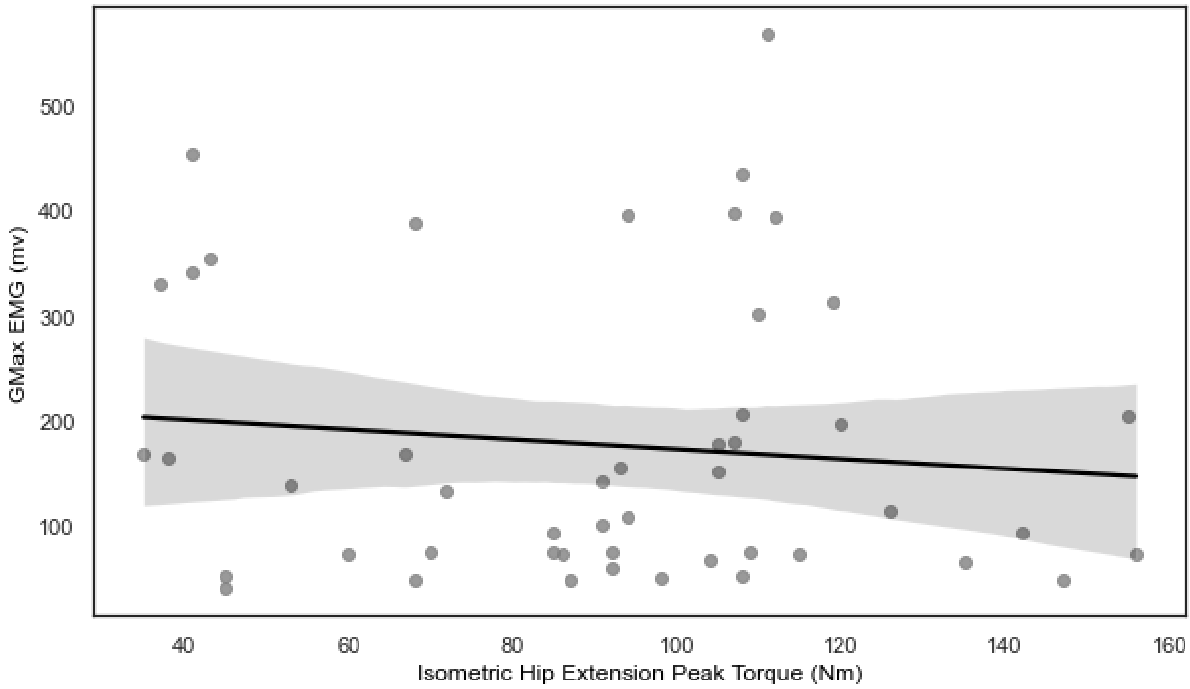


Figure 5-3 A scatterplot of the correlation between GMax peak EMG amplitudes (µV) against isometric peak torque (Nm) during hip extension. Magnitude of correlation is represented by the solid line with 95% confidence intervals represented by the shaded area.

There was no meaningful or significant (r = 0.109, p = 0.460) correlation between peak GMax EMG amplitude and peak isometric hip extensor torque. A scatterplot to represent the correlation between GMax peak EMG amplitude is presented in FIGURE 5-3, with statistical outputs presented in TABLE 5-4.

5.6 Discussion

The purpose of the study was to ascertain the within-session reliability and absolute variability of three distinct methods EMG normalisation. The MAN and IKD methods selected in the current study were based on those methods commonly reported in the EMG literature, with the GS method suggested by Contreras et al. (2015) as a simplified means of obtaining a gluteal MVIC therefore the HS method was first introduced here as a secondary objective to ascertain the magnitude, reliability and variability of a potentially more time-efficient means of achieving a hamstring MVIC without the need for application of external resistance. Finally, the study aimed to correlate peak hamstring and gluteal EMG amplitudes to knee flexor and hip extensor torques derived through isometric conditions on an isokinetic dynamometer to establish any relationship between EMG amplitude and torque output.

The primary results of the current study indicate that the MAN HIP and MAN KNEE methods produce comparable peak EMG amplitudes in the hamstring and gluteal muscles, with non-significant, trivial-small differences across methods ($p \geq 0.05$; d = 0.05 - 0.28). Although the GS method produced a comparable EMG amplitude to the MAN HIP and MAN KNEE methods, the HS produced significantly lower EMG amplitudes in comparison to all other methods of hamstring normalisation ($p \leq 0.05$; d = 0.72 - 1.0). Therefore, the initial hypothesis was partially accepted, except for the *GS* method which produced peak EMG amplitudes that were not significantly different to the MAN and IKD methods.

The findings here in relation to the magnitude of EMG amplitude do not agree with Contreras et al. (2015) that indicated that unpublished data from their laboratory demonstrated that the *GS* method elicited significantly higher peak gluteal EMG amplitudes than the MAN HIP method. Although Contreras and colleagues (2015) did not report any reliability of variability of their proposed normalisation method, they indicated that both the MAN HIP and GS methods were recorded and then, during data analysis, the reference value selected for normalisation was based on which value was higher of the two. The results of the current study indicate high levels of absolute variability associated with both the GS and MAN HIP methods, however given the good levels of reliability associated with the MAN HIP method, and only moderate reliability associated with the GS method, coupled with the lack of statically significant differences in peak amplitudes, would suggest that the GS method is ill-advised for the normalisation of gluteal muscle EMG amputees.

With regards to the MAN KNEE method for the hamstrings, the results of the current study indicated that reliability and absolute variability in the BF_{LH} was excellent and acceptable and good and acceptable in the MH, therefore the secondary hypothesis was accepted. These results indicate better reliability than previously reported by Bussey et al. (2017) which indicated good reliability of the MAN KNEE method in the left limb, but only moderate reliability in the right limb, although the authors concluded better levels of reliability based on the absolute ICC value, whereas the lower-band of the 95% CI has been considered here in comparison with the current data set. Interestingly, Bussey et al. (2017) also conducted a between-session reliability analysis of the same methods conducted across two separate testing days and reported excellent reliability of between-trial measures of the MAN KNEE in the left limb, but again only moderate reliability in the right limb. With regards to the MAN HIP method of normalisation for the gluteal muscles, Bussey et al. (2017) reported comparable results to the current data set in that within-session reliability was good-excellent (ICC 0.850 – 0.990) in both testing days, however between-session reliability was poor-excellent (ICC 0.440 - 0.980).

The results of the study indicate that researchers and practitioners should utilise the IKD HIP method as a reliable means of normalising EMG for the hamstring and gluteal muscles. In one respect, this could be seen as a time-efficient means of normalisation due to the need to only complete one single method to normalise EMG amplitudes from the hamstrings and gluteal muscles at the same time. However, the general set-up process of the IKD is somewhat time-consuming. Additionally, the use of the IKD brings about a number of accessibility issues for those without direct access, or in busy laboratory environments where multiple researchers require access to testing equipment. In research where, only hamstring EMG is obtained, the MAN HIP method seems to provide a time-efficient means of obtaining EMG amplitudes with good-excellent reliability and acceptable absolute variability. In settings where access to the IKD is not feasible, researchers should opt for the use of the MAN HIP method, given that although the %CV of both the MAN HIP and GS methods exceeded the threshold for acceptability, reliability of the MAN HIP method was found to be good, but only moderate in the GS. The unacceptable levels of absolute variability may be a limitation to the normalisation of gluteal EMG normalisation, however other authors such as Bussey et al. (2017) have reported low (≤ 9%) within-session standard error of measurement, during the normalisation of gluteal EMG during the MAN HIP method. Although the current study deemed it more appropriate to report %CV to represent absolute variability, rather than an expression of %SEM, for comparative purposes the %SEM (calculated using equation 5.1) for GMax amplitudes during the MAN HIP method was 29.2%, indicating a greater level of absolute variability and SEM in the current data set compared to that of Bussey et al. (2017). Alternative methods of gluteal normalisation such as the $Peak_{Task}$ method may be considered, but is then restricts comparisons between exercises, given the different mechanical demands and therefore metabolic and muscle excitation demands between different movements. Therefore, the researcher must give consideration to the contraction types included in the task and then apply appropriate differentiation between different contraction types (such as concentric and eccentric), given the differences in metabolic demand and likelihood of greater EMG amplitudes during a concentric contraction than an eccentric contraction where external load is matched, as previously discussed by the likes of Selseth et al. (2000).

$$SEM = \sigma\sqrt{1 - ICC}$$

$$\%SEM = \frac{SEM}{Mean} * 100$$

Equation 5.1 σ is the EMG amplitude SD, Mean is the average amplitude across trials. Absolute SEM calculated initially, to allow the calculation of %SEM.

Given that the of correlations between isometric peak torque and peak EMG amplitudes were shown to be trivial (BF_{LH} * Knee Flexor Torque, r = 0.037, p = 0.788 and BFLH * Hip Extensor Torque, r = 0.028, p = 0.851) to small (MH * Knee Flexor Torque, r = 0.165, p = 0.233 and GMax * Hip Extensor Torque, r = 0.109, p = 0.460) , with the exception of the MH during isometric hip extension (r = 0.324, p = 0.025), the results of the study indicate that there is no meaningful relationship between *isometric* peak torque during an MVIC performed on the IKD, and the expected peak EMG amplitude which supports the tertiary hypothesis.

Therefore, the peak EMG amplitude obtained during MVIC seems not to be reflective of actual force or torque output. These findings may contribute significantly to the observed lack of reliability across published EMG studies using MVIC as a reference value and may question the value of making exercise selection recommendations, based on EMG amplitudes alone, without consideration as to the mechanical or metabolic demands of the exercise, or the ability to apply external loads to such exercises.

One key example of such exercise selection recommendations can be noted from Zebis et al. (2013) that indicated that the fit-ball flexion exercise, in which participants squeeze an exercise ball between the heel of the foot and the gluteal region, via knee flexion (tantrum-type repetitive knee flexion against an exercise ball), achieved the greatest BFLH peak amplitude in comparison to other common hamstring training exercises, including the supramaximal NHE. However, there are issues with selecting an exercise such as the fit-ball flexion exercise based only on such EMG amplitude analyses. Particularly, when considering that the fit-ball flexion is a predominantly concentric exercise, (Zebis et al., 2013) there is a potential to achieve a higher level of muscle excitation compared with the eccentrically bias (Selseth et al., 2000) NHE, additionally the fit-ball flexion exercise loads the hamstrings at short MTU lengths at knee joint angles of ≥90° and therefore may not lead to maximal strength adaptations at long MTU lengths such as those experienced in the terminal swing phase of high-speed running. (Schache et al., 2012; Wing and Bishop, 2020) Finally, when considering the potential of the addition of external loads to the exercises included in the study of Zebis et al. (2013) there is likely a greater potential to increase external loads within recommendations for maximal strength training adaptation (one to six RM), (Suchomel et al., 2017) such as the RDL, which also allows for anterior displacement of the loaded barbell mass and posterior shift in centre of pressure (towards the heels) as the hips move posteriorly, which creates a higher potential for increased hip extensor and knee flexor torques, which are not considered in the majority of EMG-derived exercise selection studies.(Árnason et al., 2014; Beuchat and Maffiuletti, 2019; Bourne et al., 2017; Comfort et al., 2017; Delahunt et al., 2016; Ditroilo et al., 2013a; Guruhan et al., 2020; Narouei et al., 2018; Šarabon et al., 2019; Tsaklis et al., 2015; van den Tillaar et al., 2017; Zebis et al., 2013)

5.7 Conclusion

The key findings indicate that the peak EMG observed during an MVIC may not truly reflect the force output during the observed task. As a result, although MVIC does seem to provide a reliable within-session reference value, this value does not seem to be reflective of force output and therefore unlikely to inform expected strength adaptations in exercise studies. As a result, the exercise comparison presented in CHAPTER 6 will report normalised EMG amplitudes using the MAN HIP method, however, will develop a more thorough biomechanical framework, beyond EMG alone, upon which to inform exercise selection through the use of knee and hip joint torque estimations and estimations of muscle force contributions.

Chapter 6 A kinetic and electromyographic comparison of the Romanian deadlift and good morning exercises

6.1 Chapter Overview

This chapter presents kinetic and kinematic data of the hip and knee joints, and electromyographic data for the hamstring muscles and gluteus maximus during the Romanian deadlift and good morning exercises. Magnitudes of difference between the two exercises are presented across the entire movement waveform, rather than based on maxima values as is typically presented in the exercise comparison and exercise selection literature. The results of this chapter are then critically discussed in relation to the existing literature base and are then used to inform the exercise selection rationale for the training intervention study presented in Chapter 8.

6.2 Background

Strength training has been shown to mitigate risk factors of HSI (Bourne et al., 2017; Cuthbert et al., 2020; Ripley et al., 2022). It was determined in CHAPTERS 3-4, that strength training is a commonly utilised method in applied practice across a range of sports. Furthermore, it was reported that hip-hinge exercises, such as the RDL and good morning are widely utilised exercises programmed by practitioners with the aim of mitigating HSI risk and / or as a supplementary exercise to enhance HSR and maximal sprint running performance. However, unlike exercises like the NHE, published literature on the kinetic and electromyographic characteristics of the RDL and good morning remains relatively sparce and even those studies published in this area as associated with a number of inconsistencies, for instance the large peak knee flexions during the RDL reported by Lee et al. (2018) and the fully extended knee joint position in the GM in the study of Hegyi et al. (2019)

A broad range of research (Árnason et al., 2014; Beuchat & Maffiuletti, 2019; Bourne et al., 2017; Comfort et al., 2017; Delahunt et al., 2016; Ditroilo et al., 2013; Guruhan et al., 2020; Narouei et al., 2018; Šarabon et al., 2019; Tsaklis et al., 2015; van den Tillaar et al., 2017; Zebis et al., 2013) has been conducted in the field of exercise selection to assist practitioners in adopting an evidence-informed decision-making process to exercise selection or exercise variation. In the majority of studies in relation to hamstring-related exercise selection, researchers have focussed primarily on the use of sEMG to inform decisions (Andersen et al., 2018; Beuchat & Maffiuletti, 2019; Bezerra et al., 2013; Bourne et al., 2018; Bourne et al., 2017; Collazo et al., 2018; Comfort et al., 2017; Contreras et al., 2015; Delahunt et al., 2016; Ditroilo et al., 2013; Guruhan et al., 2020; Hegyi et al., 2018; Hegyi et al., 2019; Malliaropoulos et al., 2015; McAllister et al., 2014; Narouei et al., 2018; Schoenfeld et al., 2015; van den Tillaar et al., 2017; Williams et al., 2018). As previously discussed in CHAPTER 5, there are a number of methodological and analytical inconsistencies in the sEMG literature which influence the resultant conclusions of such studies (e.g., method of amplitude normalisation and signal processing and rectification. Furthermore, the inability of sEMG to estimate loading associated with a given exercise means that making an exercise selection decision made on sEMG alone leaves some uncertainty related to which exercises may lead to be most 'optimal' stimuli and therefore adaptations in muscle structure and function. Only a limited number of researchers (Contreras et al., 2013; Hegyi et al. 2019a; Ruan et al., 2021) have taken the exercise selection literature beyond only sEMG to consider some estimate of loading through estimations of associated joint moments during exercises at various loads. Although, like the EMG-based literature there has been various methods used to make such estimates. For instance, Contreras et al. (2013) provided rudimentary estimations of joint moments based on two-dimensional motion capture and assumed segment masses and centre of segment mass displacements. On the other hand, some authors have utilised three-dimensional motion capture with external force structures such as the NordBord (Ruan et al., 2021) or force plates (Van Hooren et al., 2022) to calculate joint moments through an inverse dynamics function. Ruan et al. (2021) have made estimates of muscle force contributions during the NHE and Van Hooren et al. (2022) also reported estimates of muscle force contributions and fascicle length changes during the single leg RDL, NHE and Roman Chair hold.

One of the key criticisms of the commonly used NHE is that it can be considered a 'knee dominant' exercise (Hegyi et al., 2019) in that the majority of torque experienced during the exercise is in the form of a knee flexor moment, with a theoretically much smaller hip extensor moment to maintain an upright torso posture. However, when the exercise is not coached appropriately, or the athlete lacks sufficient knee flexor strength to complete the exercise with an upright torso, a common compensatory mechanism is to flex at the hip during the descent. This flexion of the hip reduces to moment arm between the knee joint centre and centre of mass of the torso. As a result, the athlete can continue with a controlled descent in a position with a shorter moment arm and the additional assistance of hip extensor torque generated by the gluteal muscles and proximal hamstrings (Hegyi et al., 2019). It should be noted here that it was reported by Hegyi et al. (2019) that by performing the NHE while performing the NHE with a flexed hip joint (to 90˚) alters the length-tension relationship of the hamstrings which may be a position that allows for greater force production. On the other hand, Hegyi et al. (2019) did report a significant and very large reductions in BFLH excitation during 36-100% of normalised time and significant and large reductions in semitendinosus excitation between 45-84% and 90-100% of normalised time in a flexed position compared to a neutral position which may be indicative of an increased contribution of passive structures to net force production.

For these reasons, coaches should aim to instruct the exercise to be performed with minimal trunk or hip flexion to ensure that the hamstring group is targeted in a supramaximal nature. This criticism of the NHE as a knee dominant exercise is likely due to the biarticular nature of the hamstring muscle group and the groups contributions to large simultaneous knee flexor moments (0.53 ± 0.09 $Nm \cdot kg^{-1}$ at velocities of 3.5 $m \cdot s^{-1}$ rising to 1.76 ± 0.28 $Nm \cdot kg^{-1}$ at 8.95 $m \cdot s^{-1}$) and hip extensor moments (0.91 ± 0.17 $Nm \cdot kg^{-1}$ at velocities of 3.5 $m \cdot s^{-1}$ rising to 4.18 ± 1.26 $Nm \cdot kg^{-1}$ at 8.95 $m \cdot s^{-1}$) during the terminal swing phase of HSR actions (Schache et al., 2011). Therefore, hip-hinge exercises may provide a more ‘functionally specific’ training stimulus and may have the potential to generate simultaneous hip extensor and knee flexor moments, which may therefore increase the adaptations across the proximal and distal portions of the hamstring group, which in-turn could further mitigate the risk of HSI and enhance HSR performance. Injury risk mitigation from the use of hip hinge exercises could be enhanced given the previous findings from the likes of Sugiura et al. (2008) and Opar et al. (2015) that concentric hip extensor and eccentric knee flexor weaknesses, respectively are contribution factors to an increased risk of HSI. Additionally, Morin et al. (2015) reported significant and meaningful relationships ($p \leq 0.024 - 0.041$; R^2 0.439) between muscle excitations of the BF and the GMax and horizontal force production during sprint accelerations. Such findings may also be indicative of a need to select exercises that elicit high hamstring and gluteal muscle excitations to enhance sprint acceleration performance, alongside a potential for reduced injury risk.

The RDL is commonly utilised within applied practice as observed in CHAPTER 4, however several practitioners also identified that the movement complexity associated with a loaded hip hinge can often be challenging for the athlete, particularly if the athlete has not performed the exercise before. Furthermore, it was noted that grip strength (unless using lifting straps) can often limit an athlete’s ability to perform the RDL as grip strength may fail, even before the athlete has loaded the barbell to a sufficient load to achieve a maximal strength training stimulus in the posterior chain. Therefore, although utilised to a lesser extent, the GM may offer a kinematically similar loading strategy to the RDL. While both the RDL and GM involve a hip hinge action with the knee joint in slight flexion (Kraemer et al., 1982, McAllister et al., 2014, Vigotsky et al., 2015), the GM requires the barbell to be positioned in a low-bar position, rather than the clean grip used in the RDL (Ross et al., 2023). Therefore, the GM may mitigate the issues with grip strength associated with the RDL (if lifting straps are not used), however the barbell is displaced more anterior relative to the hip joint centre than in the RDL. As a result of the larger anterior barbell displacement in the GM than in the RDL, the moment arm between the centre of mass of the barbell and the hip and knee joint centres would be larger in the GM than the moment arm between the centre of mass of the barbell and the hip and knee joint centres in the RDL. Therefore, if the two exercises were performed in load-matched conditions, the knee flexor and hip extensor moments required to complete the GM would be higher than in the RDL. However, given that participants would be expected to be able to lift larger absolute loads in the RDL (McAllister et al., 2015), this difference in load lifted is likely due to the shorter moment arm. It is not yet known if comparable joint moments can be achieved in the GM compared to the RDL at comparable relative loads, even though the absolute loads between the two exercises likely differ. As joint moments are often used as a proxy for how adaptations in muscle strength may occur in response to a given exercise (Lee et al., 2018, Van Hooren et al., 2022), if comparable joint moments can be achieved in the GM compared with RDL at lower absolute loads, this may offer practitioners scope to achieve similar adaptations to training while exposing their athletes to lower loads and mitigating potential barriers to hip-hinge exercises that may exist with the RDL such as limited grip strength, upper limb injury or for para athletes such as those following upper limb amputation.

Both the RDL and GM load the hamstring group in the proximal and distal positions due to the hip hinge movement and the maintenance of a slightly flexed knee. These positions result in the centre of mass of the barbell and resultant ground reaction force vector being positioned anterior to both the knee joint and hip joint throughout the movement, resulting in a simultaneous knee flexor and hip extensor moment. This loading strategy may therefore better mitigate HSI risk factors in relation to the common MOI during HSR which includes simultaneous hip flexion and knee extension during the mid-late swing phases of the HSR gait cycle (Chumanov et al., 2011, Kenneally-Dabrowski et al., 2019).

As previously discussed, (CHAPTER 5) Lee et al. (2018) estimated joint torque during the RDL, however the amount of knee flexion demonstrated by lifters in Lee et al. (2018) means that the knee joint moments reported are likely underestimated compared to if the exercise performed was better representative of how the exercise has been described elsewhere (Frounfelter, 2000).

6.3 Aims and Hypotheses

The aim of the current study was to compare sEMG amplitude of the hamstring and gluteus maximus muscles, and joint moments acting upon the hip and knee during the RDL and good morning. The objective was to develop a biomechanically robust basis upon which practitioners could make exercise selection decisions, beyond sEMG amplitudes alone. It was hypothesised that although higher absolute loads would be lifted in the RDL, the increase in anterior displacement of the barbell during the good morning (and therefore larger moment arm between barbell centre of mass and centre of mass of the hip and knee joints) would mitigate differences in absolute loads and therefore result in no significant differences in normalised joint moments or muscle excitations between the two exercises.

6.4 Methods

6.4.1 Participants

Prior to participant recruitment, a 1D *a priori* sample size estimation was conducted in Python (version 3.11, Anaconda Python Distribution, Computer software) as per Robinson et al. (2021). Currently the use of 1D waveform analyses in exercise comparisons is limited, with the majority of authors making inferences based on maximum values (e.g., peak moments or peak EMG amplitudes). As suggested by Robinson et al. (2021) the required samples for waveform analyses are larger than those needed for traditional 0D null-hypothesis testing. Therefore, to calculate the minimum required sample for the waveform analyses in the current study, the smallest worthwhile effect was calculated from those studies that reported standard deviations from normalised peak EMG amplitudes (Lee et al., 2018; Hegyi et al., 2019; Bezerra et al., 2013; Kawama et al., 2020 and Wright et al., 2999). Only EMG amplitudes were used for the smallest worthwhile effect calculated as only Lee et al. (2018) have previously reported kinetic data for the RDL and kinetic data for the GM are not currently available. For those studies that did not directly report the standard deviations, they were derived from the published figures using WebPlotDigitizer (version 5.1) (Rohatgi. 2015) where possible. Once the average standard deviation had been calculated this was multiplied by 0.2 to calculate the smallest worthwhile effect. Alpha level was set to 0.05, with a desired power of 0.8 and a smallest worthwhile effect of 2.73 which revealed a minimum required sample of n = 12. Fifteen physically active male volunteers were recruited to take part in the study. Participants were recruited to be free from any lower limb injury in the six-month period prior to data collection, with no history of lower limb surgery (e.g., anterior cruciate ligament reconstruction). Participants were required to be physically active which was defined as taking part in strenuous physical activity for a minimum of 30 minutes, three times per week, which included resistance training. Participants were in good overall physical health, based on completion of a health questionnaire prior to any data collection (APPENDIX 3.0). All participants provided written informed consent to take part in the study and were allowed at least 24 hours from receiving a participant information sheet before deciding whether they wished to participate. Institutional ethical approval (HSR1718-108) was granted prior to any participant recruitment or data collection.

Table 6-1 Participant characteristics, presented as means and (standard deviations).

Age (years)	Body Mass (kg)	Height (m)	Good morning 5 RM load (kg)	RDL 5 RM Load (kg)
23.11	87.68	1.82	48.89	79.44
(4.81)	(12.35)	(0.03)	(12.94)	(15.90)

6.4.2 Research Design

A cross-sectional comparison design was employed, whereby a group of resistance trained individuals performed each exercise in a randomised order with joint kinematics, kinetics and muscle excitations were compared.

6.4.3 Data Collection

Each participant attended the laboratory on three separate occasions. Upon arrival to the testing laboratory, participants completed a warm-up for five-minutes of stationary cycling at a self-selected moderate pace followed by a set of ten dynamic legs swings of each leg and forward lunges on each leg. The first testing day consistent of repetition maximum testing and then the individual GM or RDL testing sessions were completed on two separate testing days, separated by a minimum of 72 hours. The order in which exercises were performed was randomised using an online random list order generator (https://www.random.org). Once the order of exercises was established, these were split across two separate testing days (e.g., RDL day one, good morning day two).

Testing day one started with a warm-up as stated above, followed by a demonstration of both exercises, they were to perform on that given testing day along with a verbal description. For the RDL and good morning, five repetition maximum (5 RM) was established as follows. All participants started with a single set of five repetitions of the first exercise with an unloaded (20 kg) 7' barbell. Following this set, the barbell was loaded to a load of approximately 50% of the participants anticipated 5 RM. Participants completed incremental sets of five repetitions of the exercise until their 5 RM was established. Incremental sets were performed by increasing barbell load by five to ten kg per set with three to five minutes rest between sets. 5 RM was determined when the participant either reached a load where they could not perform more than five repetitions in a set or at the point where they were no longer able to replicate the proper technique described by Frounfelter (2000) for the RDL or by Kraemer et al. (1982) and Ross et al. (2023) for the GM.

For the exercise testing days, a set of 31 individual reflective markers were used to create a static model of each participant and to define the joint coordinate system as well as a set of four clusters positioned on each thigh and each shank to track the thigh and shank segments. A full breakdown of marker placements can be found in TABLE 6-2 with a visual representation presented in FIGURE 6-1. The static model was captured, and joint coordinate system was defined using a static trial in which the participant stood in the capture area over the force plates in upright standing with the arms abducted for a period of at least ten capture frames. Following the static trial, the trial was visually inspected to ensure that there was no drop-out of markers and the automatic identification of markers (AIM) model was applied to ensure all marker positions were correctly identified. Once the static trial was complete, the markers at the malleoli and femoral epicondyle were removed as they were not needed in the visual 3D model for the motion trials once the joint coordinate systems had been defined.

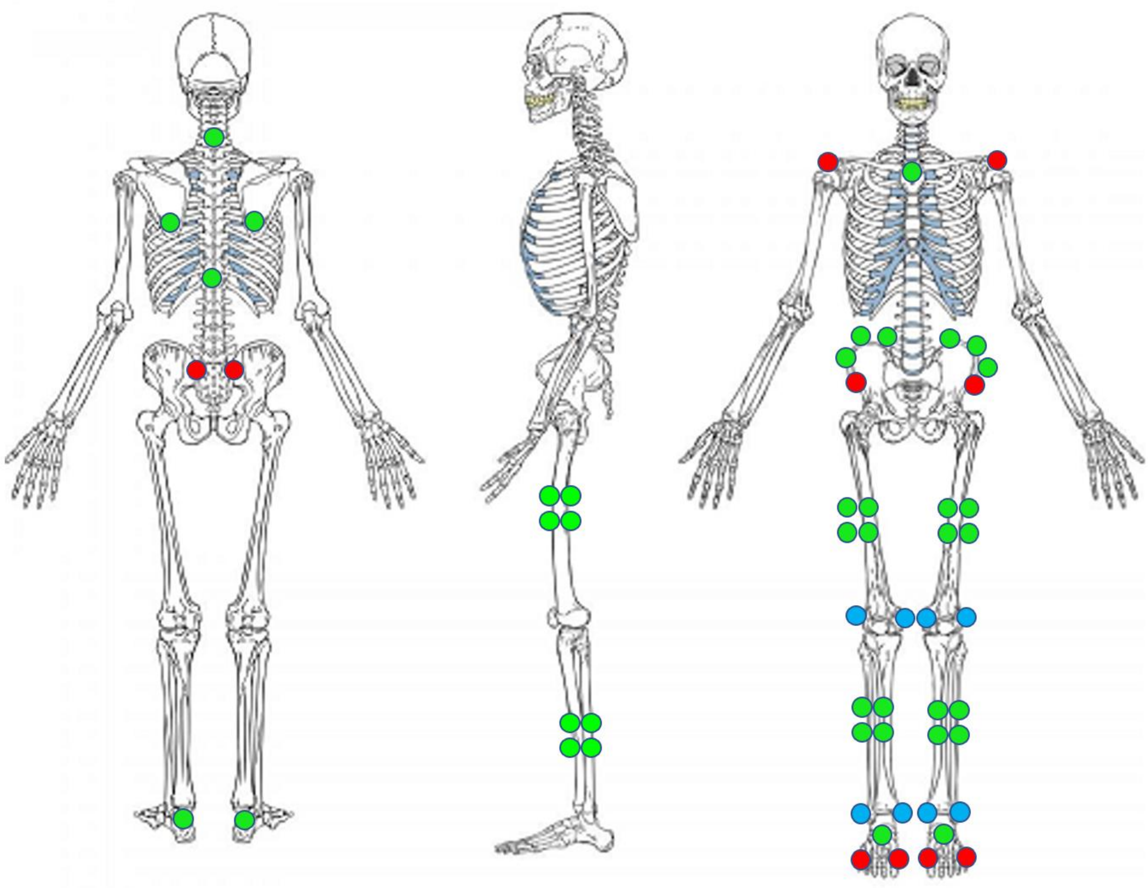


Figure 6-1 Illustration of the reflective marker locations used to track skeletal movements of participants. The red markers represent markers that were used to both define a segment location and track movement of the segment, the green markers represent markers that were used to segment tracking only and blue markers represent those that were used only for segment definition.

Following the application of reflective markers, sEMG electrodes were applied to the BFLH, MH and GMax of both legs as described in and in-line with the SENIAM guidelines. Prior to electrode placement, the skin was prepared by shaving the area over which the electrode would be placed, the shaved area was then cleansed with an alcohol wipe to minimise any impedance between the skin-electrode interface. Electrode placement involved participants in a prone position on a plinth. BF application involved passive flexion of the participants knee to 90˚. A measurement was made between the ischial tuberosity and lateral tibial condyle. The electrode was placed at 50% of the distance between the two landmarks along the presumed orientation of muscle fibres. MH electrode placement was made with the knee remaining in 90° of passive flexion. The electrode was placed at 50% of the distance between the ischial tuberosity and medial tibial condyle, in the direction of the presumed orientation of the muscle fibres. GM electrode application involved the participant in a prone position with the hip in 0° of extension. The electrode was placed at 50% of the measured distance between the greater trochanter and sacrum, in the presumed direction of the muscle fibres. Following the application of the sEMG electrodes (Delays Trigno, Greater Manchester, United Kingdom), a five-second MVIC was conducted via a prone lying isometric hip extension effort with the knee joint flexed to 55° as described by Ross et al. (2019; CHAPTER 5). Participants were instructed to exert maximal effort against a resistance applied to the posterior distal thigh by the researcher for five seconds, during which verbal encouragement was provided.

Table 6-2 Description of the individual marker locations used to define and track skeletal segments.

Segment	Segment Definition Markers	Additional Segment Tracking Markers
Foot	1st Metatarsal Head 5th Metatarsal Head Medial Malleoli Lateral Malleoli	Calcaneus 2nd Metatarsal Base
Shank	Medial Malleoli Lateral Malleoli Medial Femoral Epicondyle Lateral Femoral Epicondyle	Shank Cluster (x4)
Thigh	Medial Femoral Epicondyle Lateral Femoral Epicondyle (Proximal segment defined by hip joint centre of coda pelvis derived from pelvis definition)	Thigh Cluster (x4)
Coda Pelvis	Anterior Superior Iliac Spine Posterior Superior Iliac Spine	Iliac Spine Cluster (x3)
Rigid Torso	Posterior Superior Iliac Spine Acromion Process	10th Thoracic Spinous Process 7th Cervical Spinous Process Inferior Angle of Scapula Sternal Notch

A Visual 3D pipeline was used to automate the process of signal processing and filtering of 3D marker trajectories, force data and sEMG, computation of model-based data such as joint angles and moments and to define the start and end of each repletion across all exercises.

The model template was applied to each individual motion file and participant height, body mass and barbell mass were input into the pipeline for the purposes of normalising moments to height and system mass (sum of body and barbell masses). The interpolate function was used to fill any gaps in marker trajectories over a maximum of ten frames. Force data and marker trajectories were high-pass filtered at 25 Hz and 15 Hz, respectively. Joint angles for the ankle were defined using the foot segment with the shank as the reference segment to define foot rotation about the shank, the knee joint was defined using rotation of the shank around the thigh and the hip joint was defined as rotation of the thigh around the pelvis. As the Delsys Trigno system reports EMG amplitude in volts, the pipeline using the multiply by constant function to convert volts to microvolts for consistency with the majority of sEMG literature. A root mean square function was then applied to the EMG data in microvolts across a 200 ms moving average window.

To define the start and end of each repetition for the RDL and GM, participants were instructed to remain as still as possible for a period of approximately one second at the start of each repetition. This was to allow for the start of each repetition to be defined as when hip joint angular velocity exceeded 0˚·s, with the end of the eccentric phase defined by the position of maximum hip joint flexion and the end of each repetition defined as angular velocity returning to 0˚·s.

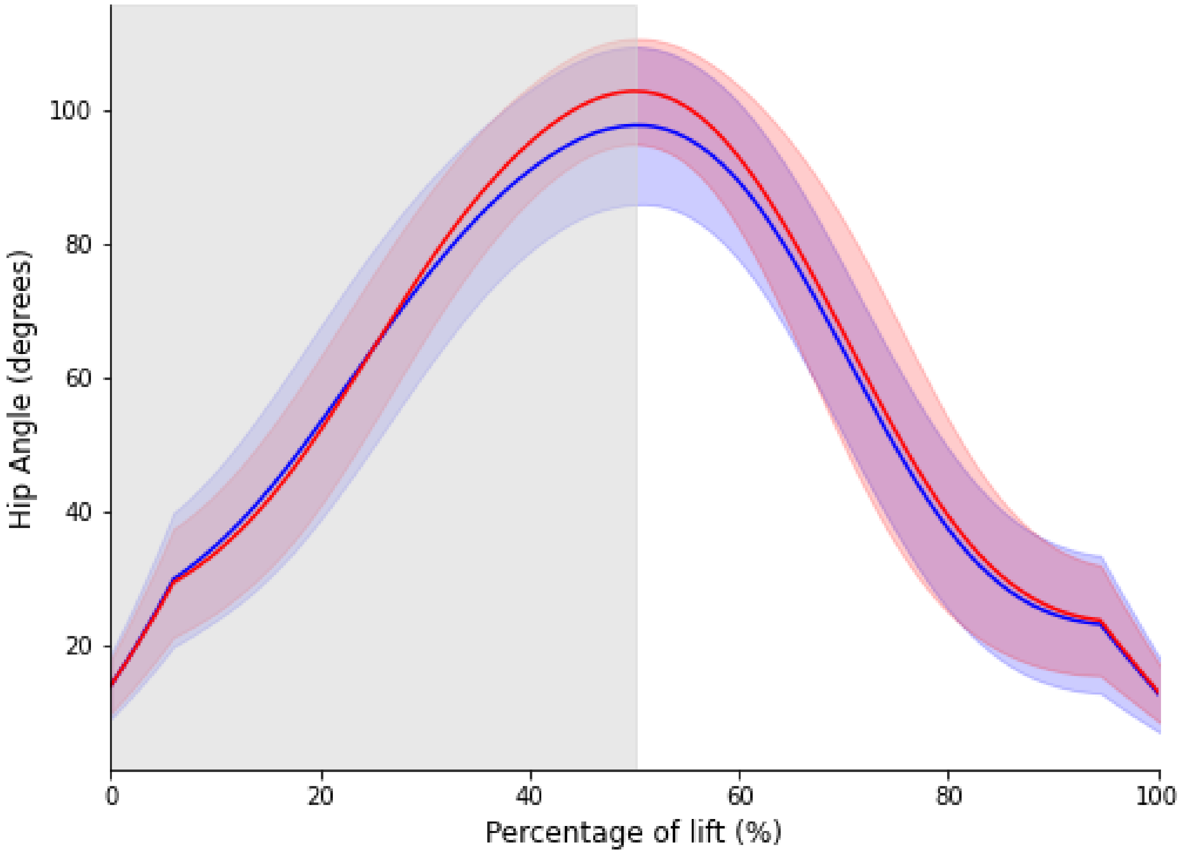
To control for differences in absolute load lifted between the two lifts, body mass and standing height of the participants, all joint moments were normalised and are presented as Newton-metres, per kilogram of system mass per metre of standing height (Nm·kg·m).

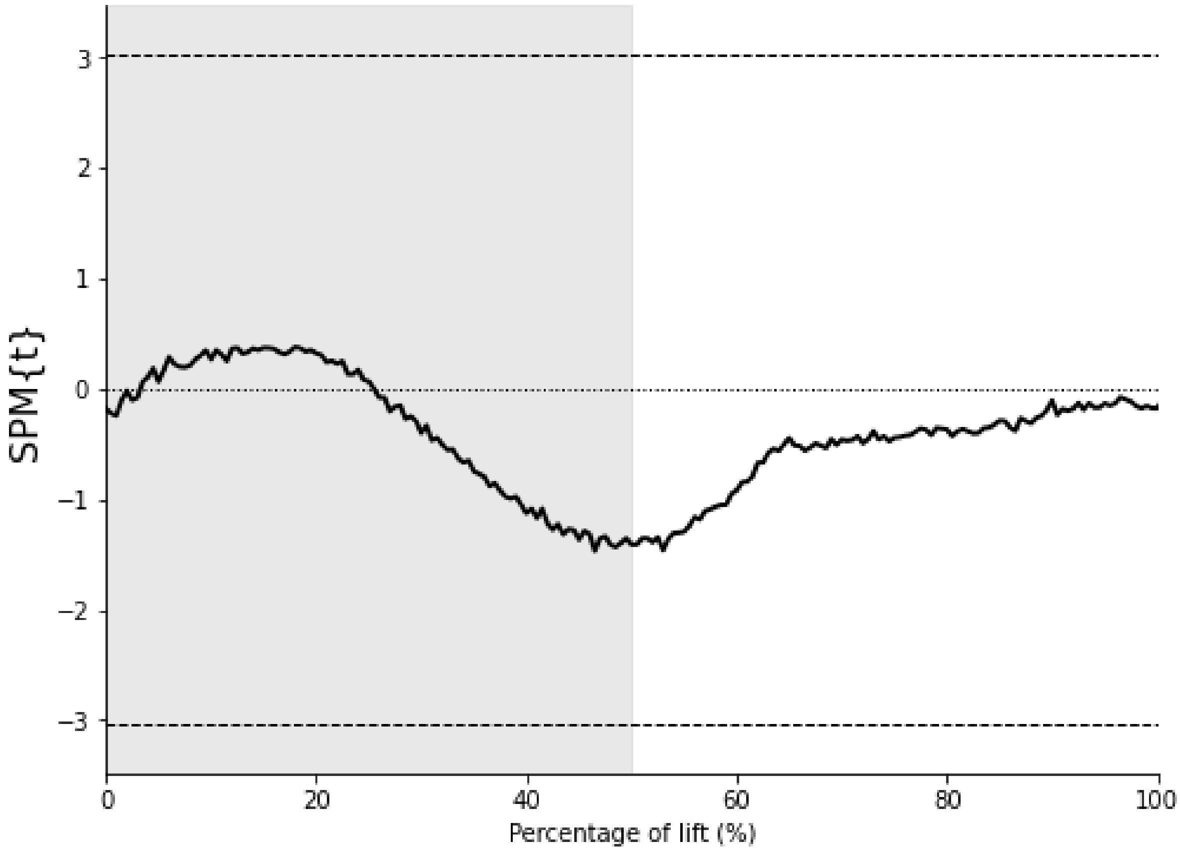
6.4.4 Statistical Analyses

Joint angles and moments were time normalised between 0% and 100% of the total lifts with 50% representing the end of the eccentric phase. Differences between joint kinematics and kinetics between the two lifts were compared using paired samples t-tests with statistical parametric mapping (SPM). SPM was undertaken in Python 3.1.1 (Anaconda Python Distribution, Computer software) using the opensource one-dimensional statistical parametric mapping package (spm1d.org). The alpha level for SPM analysis was set at $p < 0.05$. Hedges *g* effect sizes were calculated on a point-by-point basis over the entire lift to estimate the effect size of the difference between lifts. Magnitude of effect was interpreted on the following scale: *trivial* ≤0.19, *small* 0.20 – 0.59, *moderate* 0.60 – 1.19, *large* 1.20 – 1.99, *very large* ≥2.00.

6.5 Results

6.5.1 Joint Kinematics





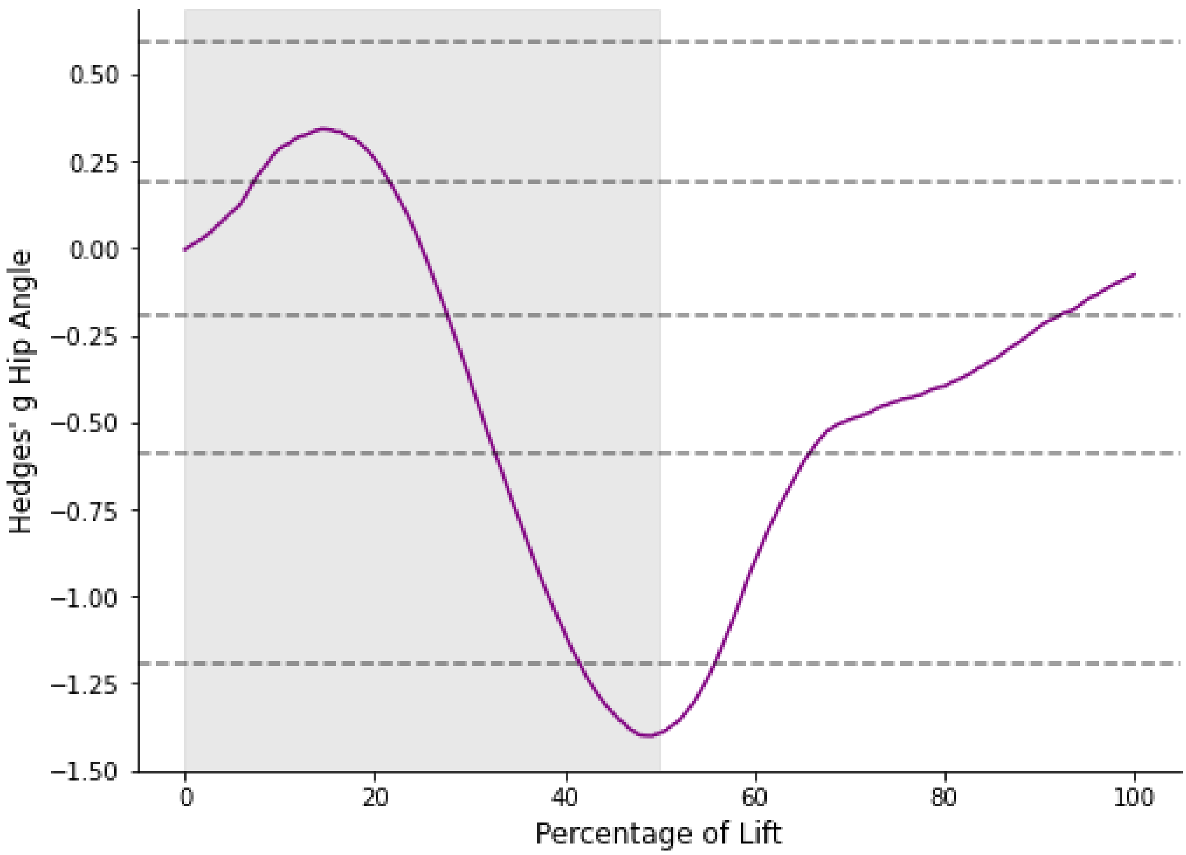
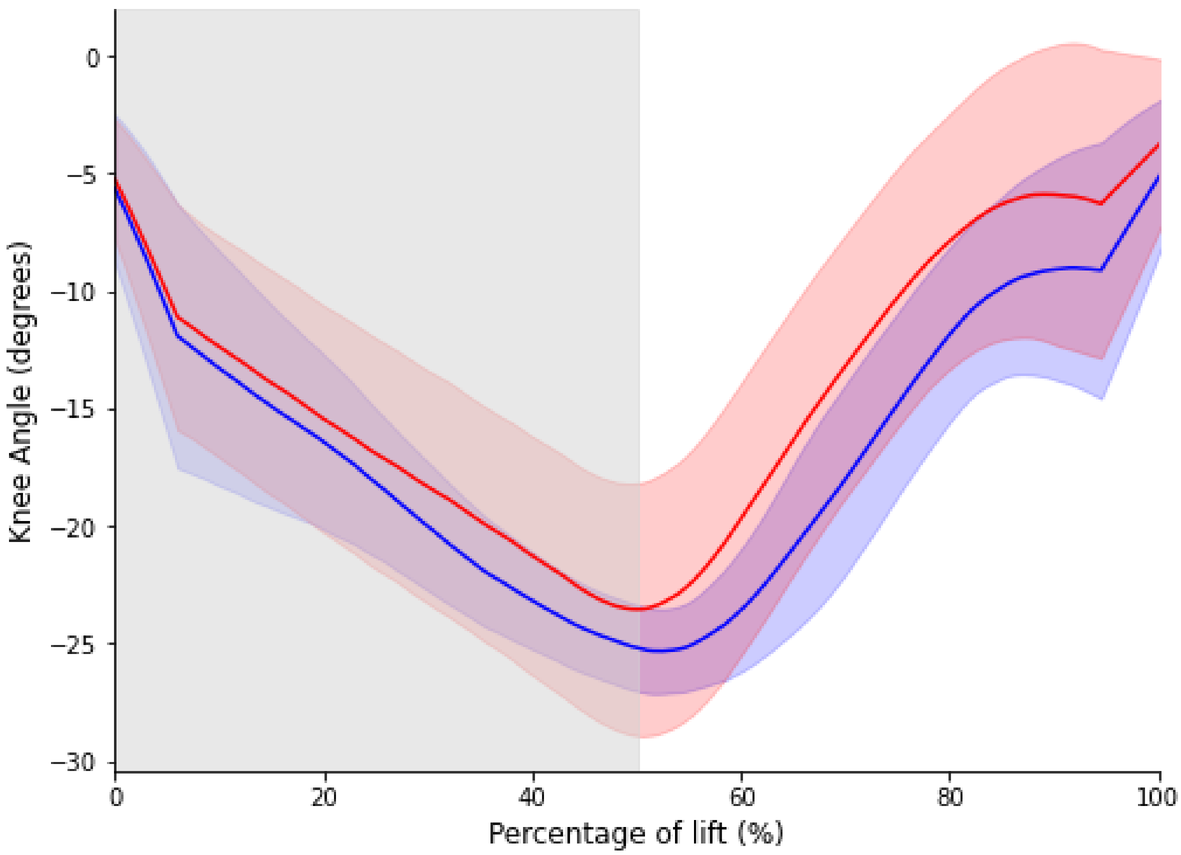
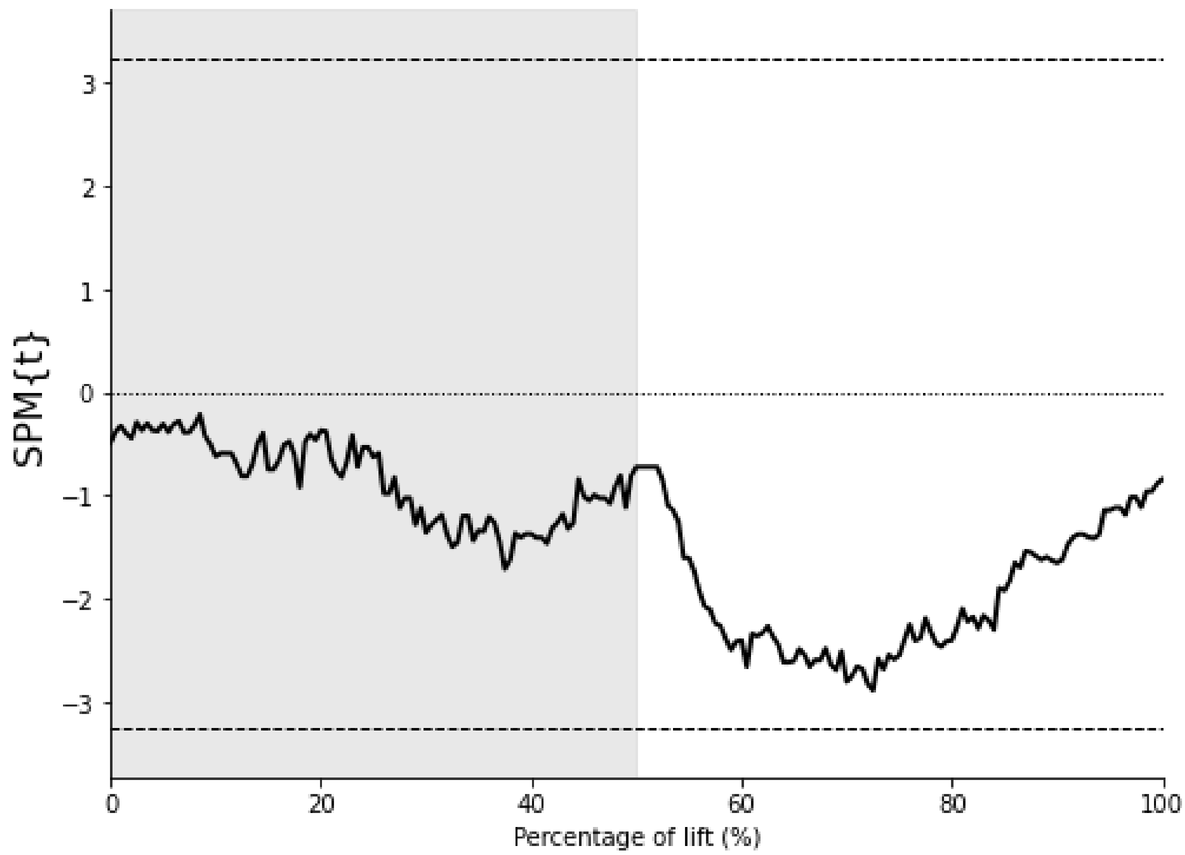


Figure 6-2 Time normalised hip angles (top) for the good morning (blue) and RDL (red). Zero degrees would represent a neutral hip joint position, with positive values representing hip flexion. Group means are represented by the solid lines with the upper the lower 95% Cis represented by the shaded areas. The t-statistic across normalised time (middle) is presented between the two lifts across normalised time. The Hedges g effect size is plotted across normalised time (bottom) with the horizontal dashed lines representing the thresholds of magnitude of effect. The grey shaded area between 0-50% on the X-axis of each plot shows the eccentric (lowering) portion of the lifts, with the white area between 50-100% of each plot representing the concentric (raising) portion of the lifts.

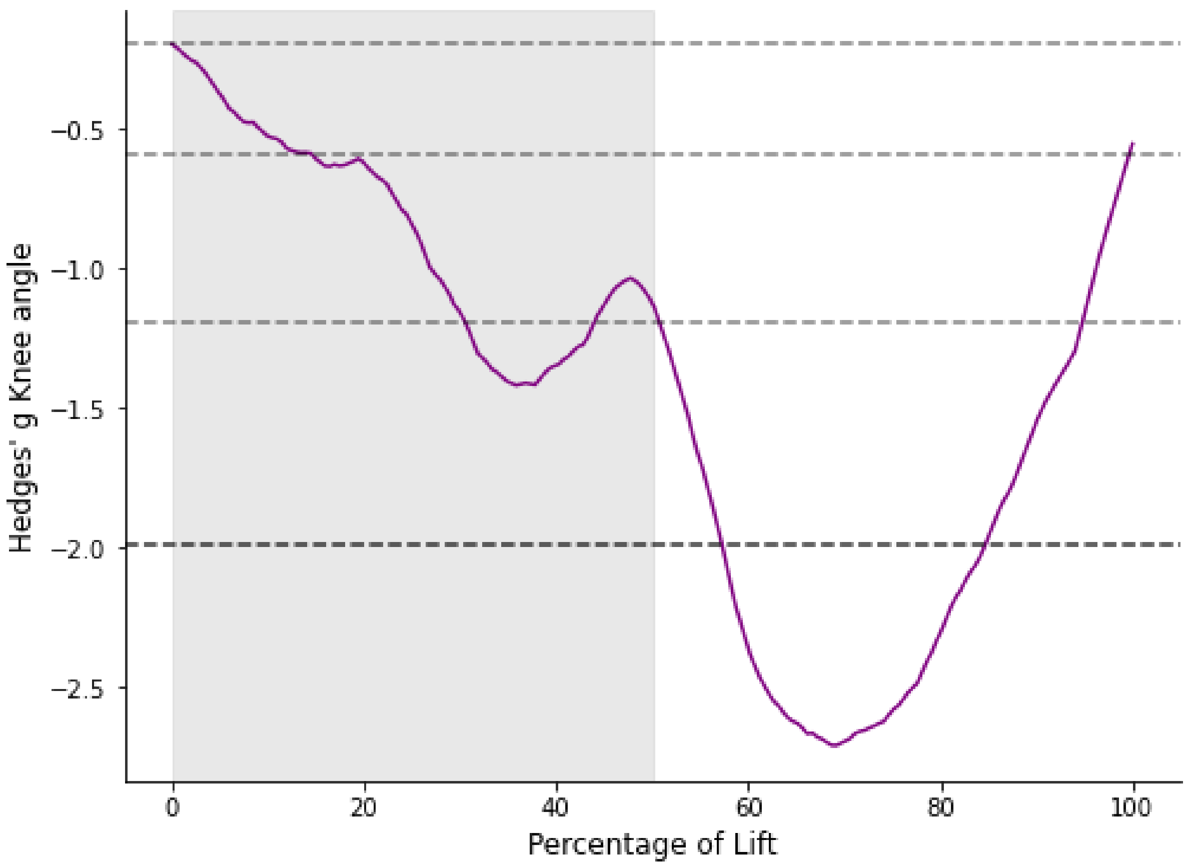
There was no significant ($p \geq 0.05$) difference between hip joint angles between the two lifts at any point across normalised time (FIGURE 6-2), however between 40-60% of normalised time, there were moderate-large increases in hip flexion angle in the RDL compared to the GM.



Knee Angle (degrees)
0
−5
−10
−15
−20
−25
−30
0
20
40
60
80
100
Percentage of lift (%)



SPM{t}
3
2
1
0
−1
−2
−3
0
20
40
60
80
100
Percentage of lift (%)

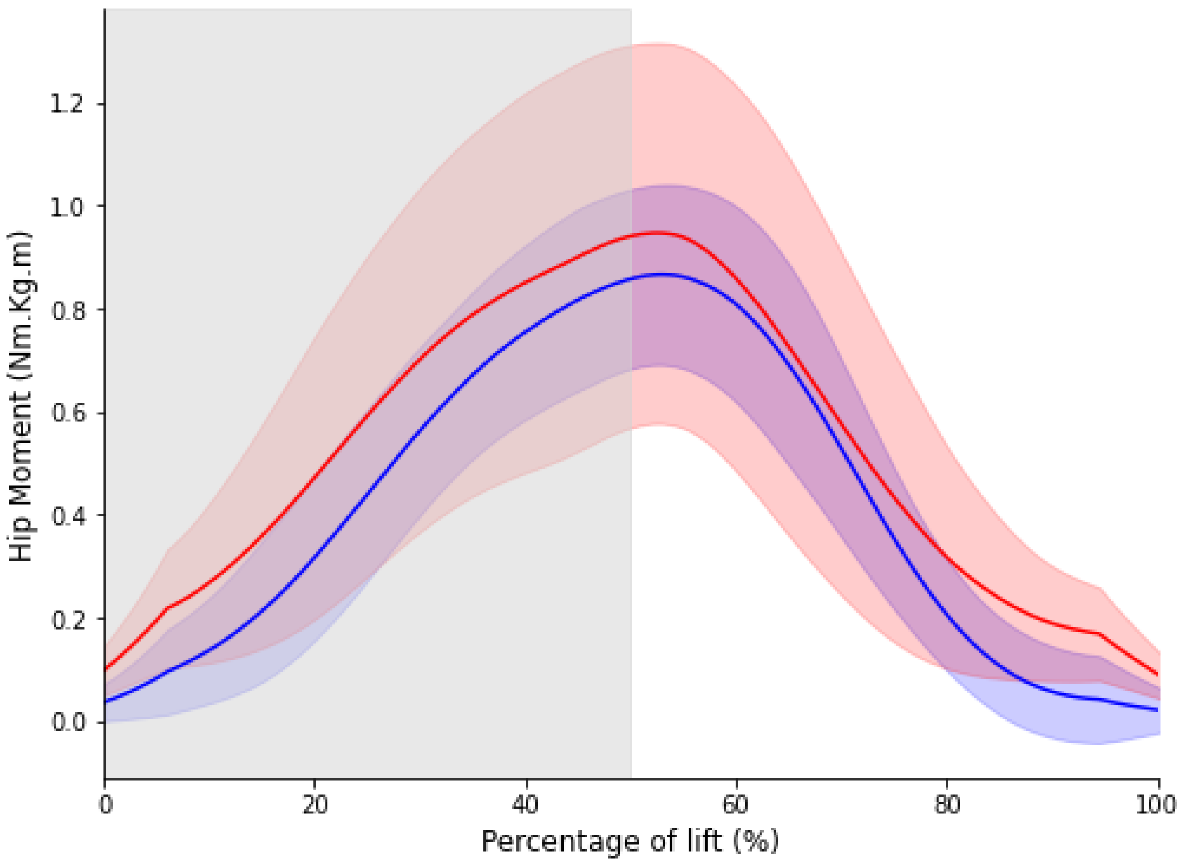


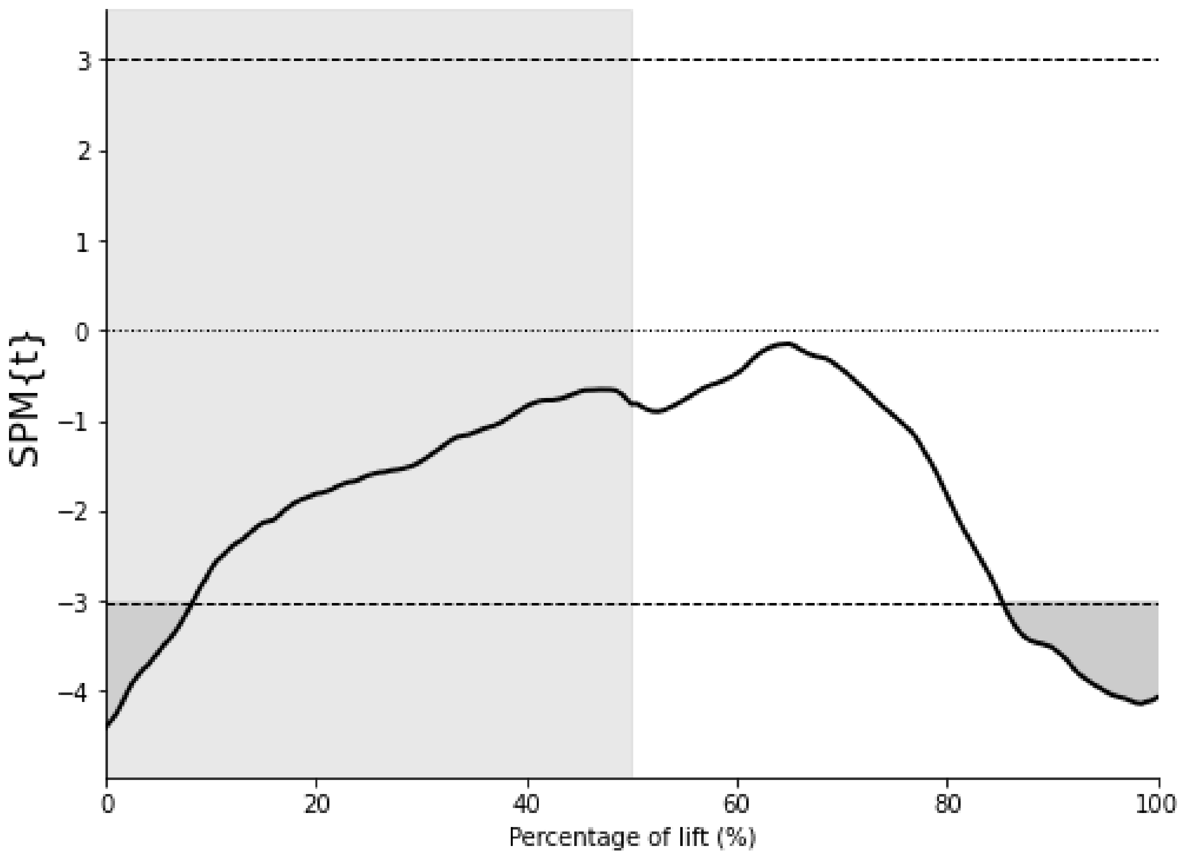
Hedges' g Knee angle
−0.5
−1.0
−1.5
−2.0
−2.5
0
20
40
60
80
100
Percentage of Lift

Figure 6-3 Time normalised hip moments (top) for the good morning (blue) and RDL (red). Zero degrees would represent an extended knee joint position, with negative values representing knee joint flexion and positive values would represent hyper-extension of the joint. Group means are represented by the solid lines with the upper the lower bound 95% CIs represented by the shaded areas. The t-statistic across normalised time (middle) is presented between the two lifts across normalised time. The Hedges g effect size is plotted across normalised time (bottom) with the horizontal dashed lines representing the thresholds of magnitude of effect. The grey shaded area between 0-50% on the X-axis of each plot shows the eccentric (lowering) portion of the lifts, with the white area between 50-100% of each plot representing the concentric (raising) portion of the lifts.

There was no significant ($p \geq 0.05$) difference between knee joint angles between the two lifts at any point across normalised time. However, magnitude of knee flexion in the GM ranged from small-large during the eccentric phase of the lifts but was large-very large between 50-94% of normalised time, before returning to moderate during the final 6% (i.e., 94-100%) of normalised time.

6.5.2 Joint Kinetics




SPM{t}
3
2
1
0
−1
−2
−3
−4
0
20
40
60
80
100
Percentage of lift (%)

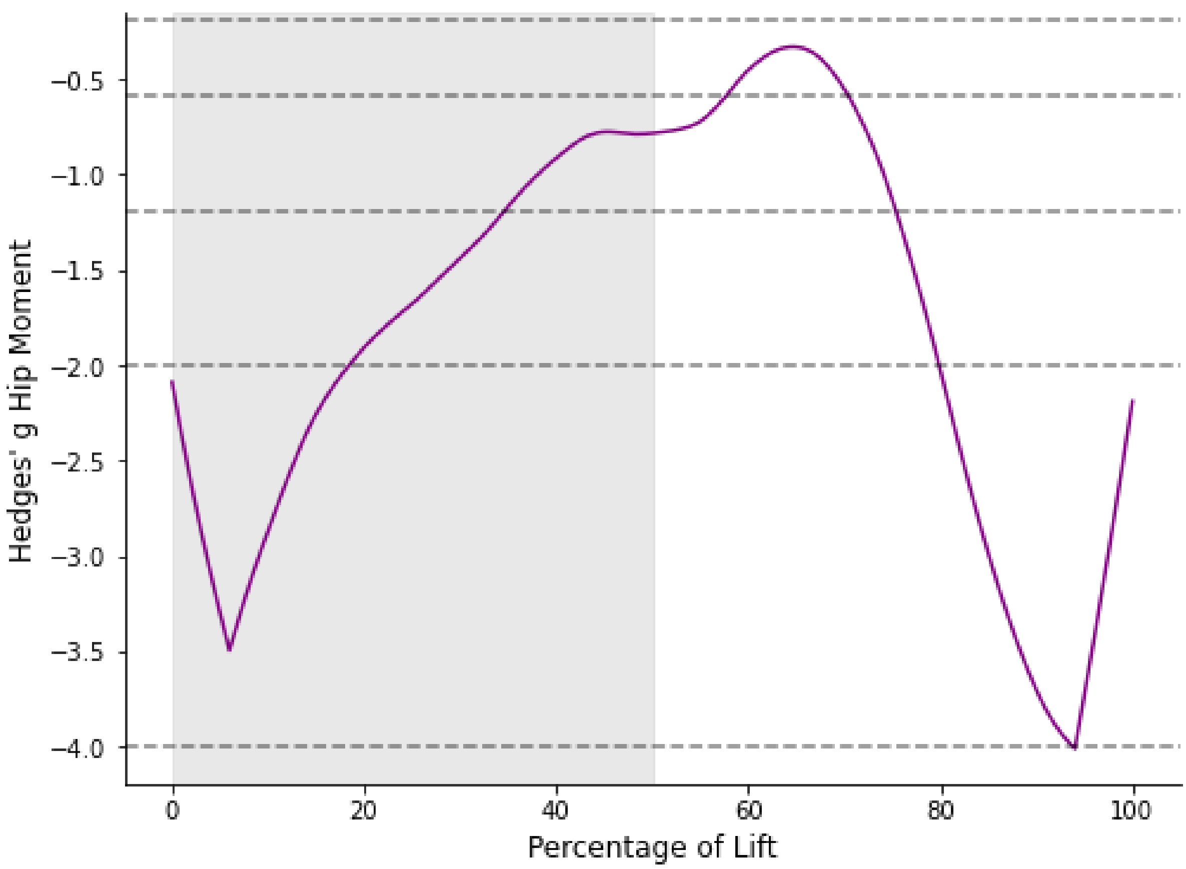
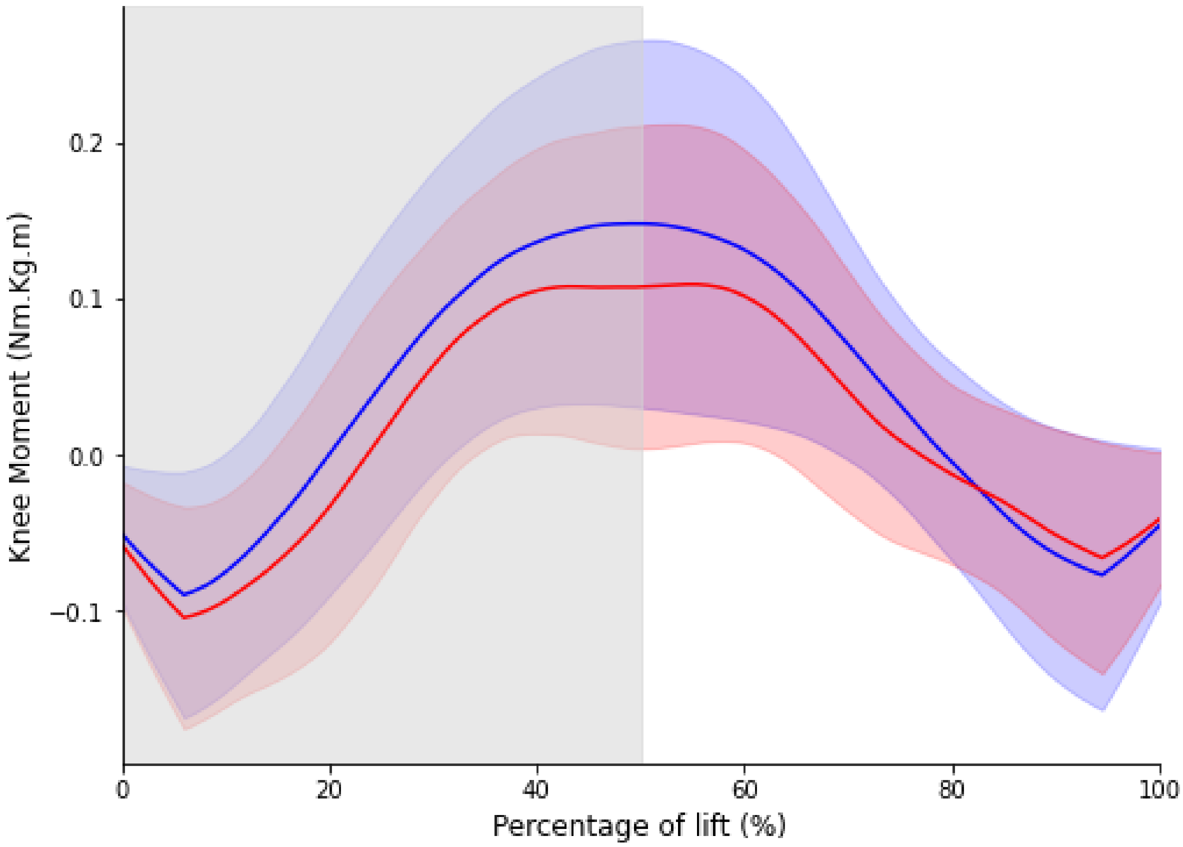
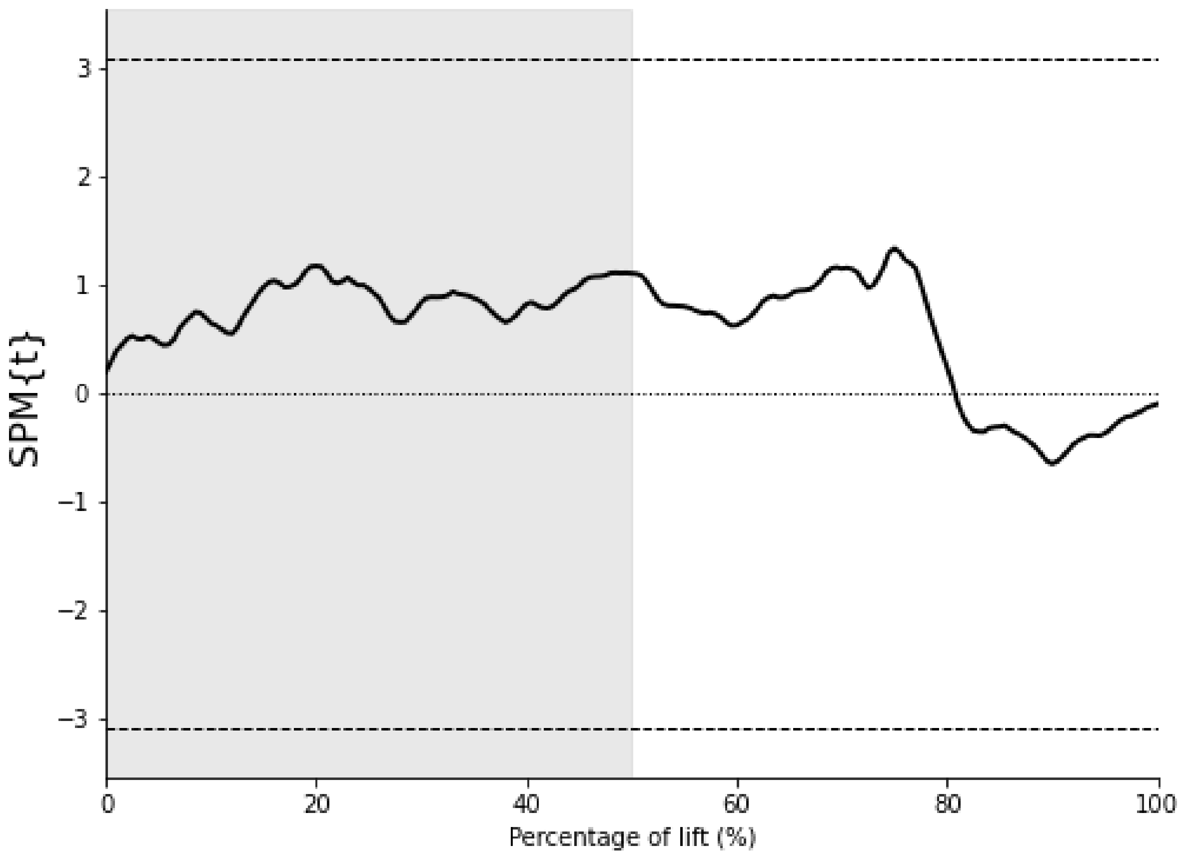

Hedges' g Hip Moment
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
0
20
40
60
80
100
Percentage of Lift

Figure 6-4 Time normalised hip moments (top) for the good morning (blue) and RDL (red) with positive values representing a hip extensor moment and negative values representing a hip flexor moment. Group means are represented by the solid lines with the upper the lower bound 95% CIs represented by the shaded areas. The t-statistic across normalised time (middle) is presented between the two lifts across normalised time. The Hedges g effect size is plotted across normalised time (bottom) with the horizontal dashed lines representing the thresholds of magnitude of effect. The grey shaded area between 0-50% on the X-axis of each plot shows the eccentric (lowering) portion of the lifts, with the white area between 50-100% of each plot representing the concentric (raising) portion of the lifts.

The hip extensor moment was lower in the GM between 0-7% of normalised time, which was significant and very large. (p = 0.03 $g \geq 2.00$). Similarly, the hip extensor moment was lower in the GM between 85-100% of normalised time, which was also significant and very large (p = 0.02; $g \geq 2.00$). There were no significant differences in hip joint moment at any other time points between the two lifts ($p \geq 0.05$).




SPM{t}
3
2
1
0
−1
−2
−3
0
20
40
60
80
100
Percentage of lift (%)

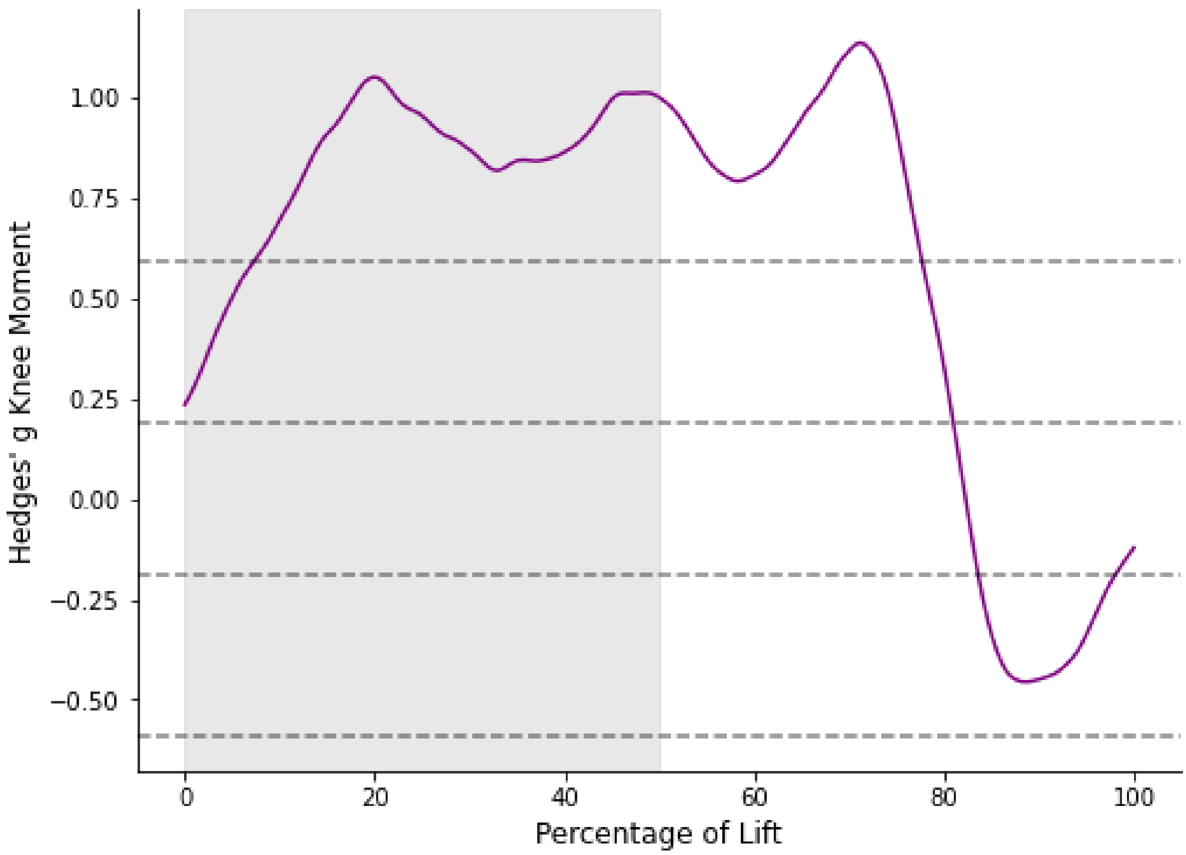
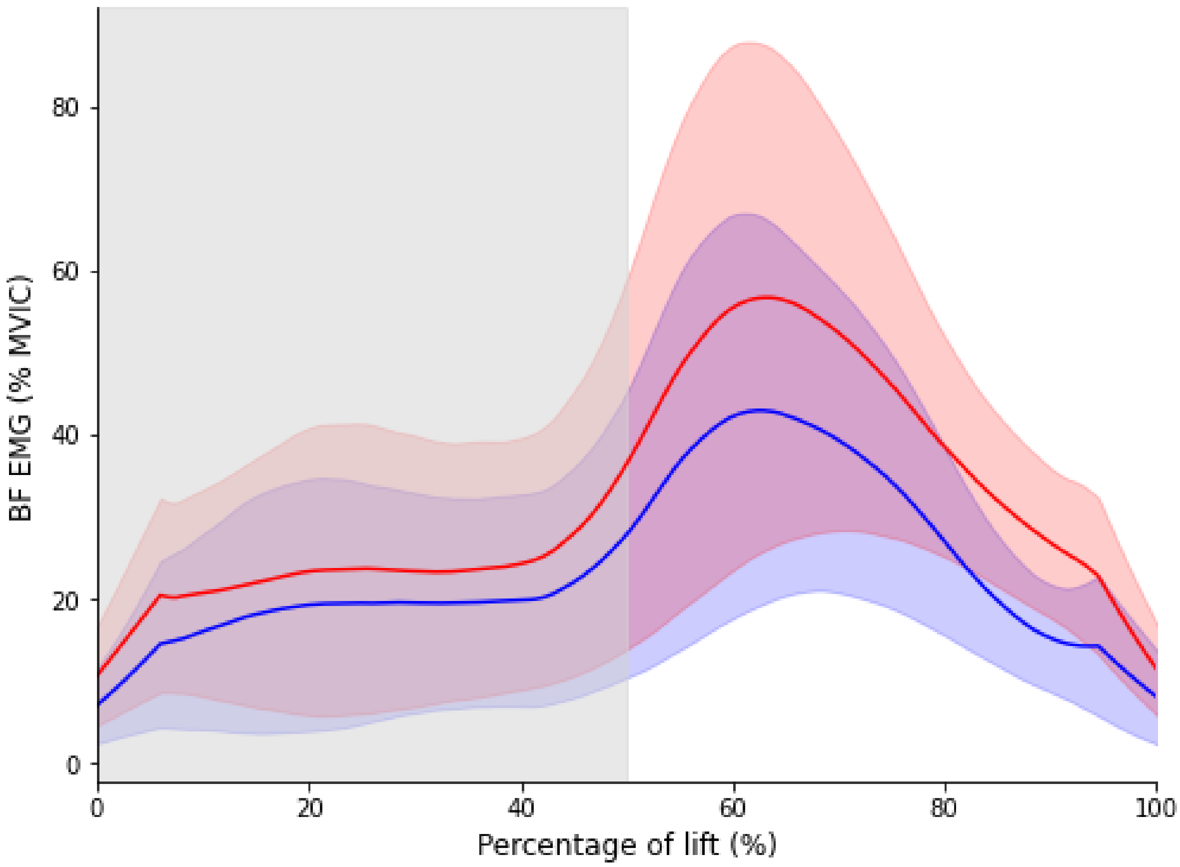
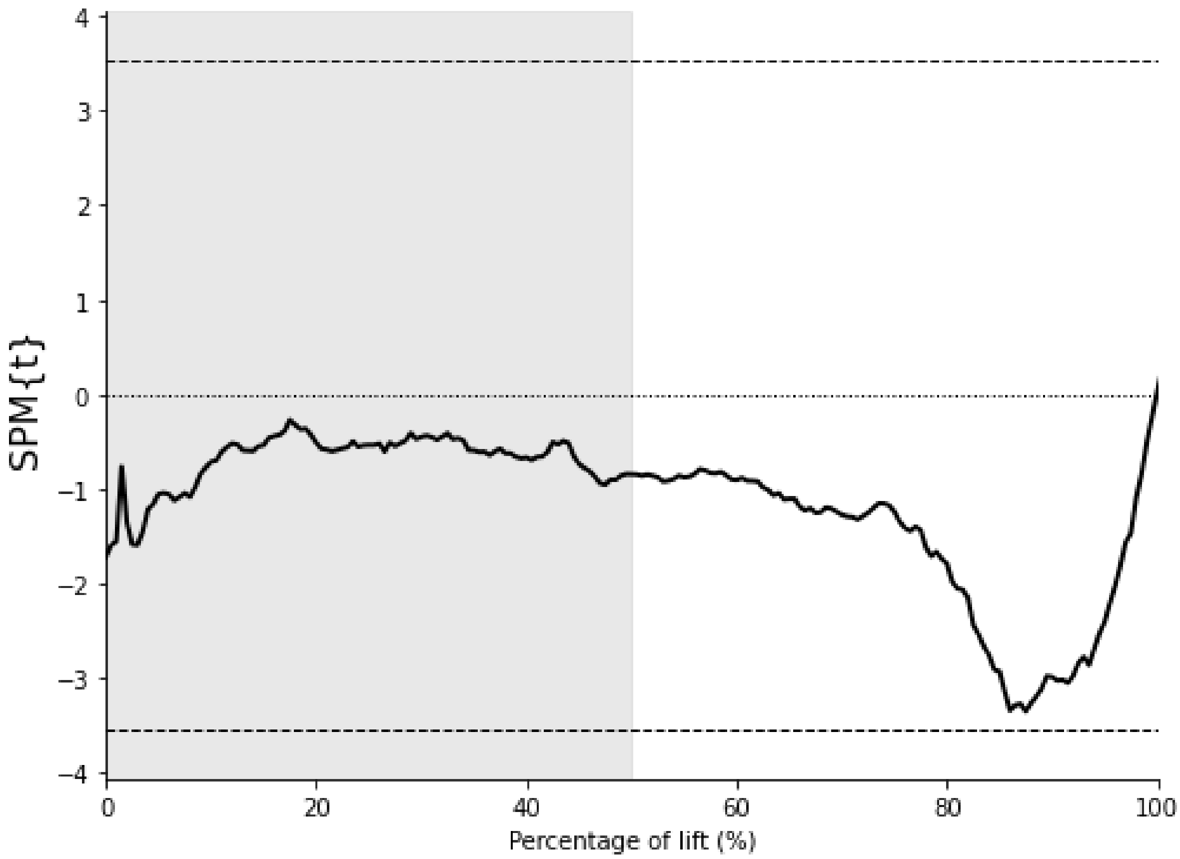


Figure 6-5 Time normalised knee moments (top) for the good morning (blue) and RDL (red) with positive values representing a knee flexor moment and negative values representing a knee extensor moment. Group means are represented by the solid lines with the upper the lower bound 95% CIs represented by the shaded areas. The t-statistic across normalised time (bottom) is presented between the two lifts across normalised time. The Hedges g effect size is plotted across normalised time (bottom) with the horizontal dashed lines representing the thresholds of magnitude of effect. The grey shaded area between 0-50% on the X-axis of each plot shows the eccentric (lowering) portion of the lifts, with the white area between 50-100% of each plot representing the concentric (raising) portion of the lifts.

There was no significant ($p \geq 0.05$) difference between knee joint moments between the two lifts at any point across normalised time. However, between 0-7% of normalised time and between 7-77% of normalised time, the knee flexor moments were higher in the GM with magnitudes of small and moderate, respectively.

6.5.3 Muscle Excitation





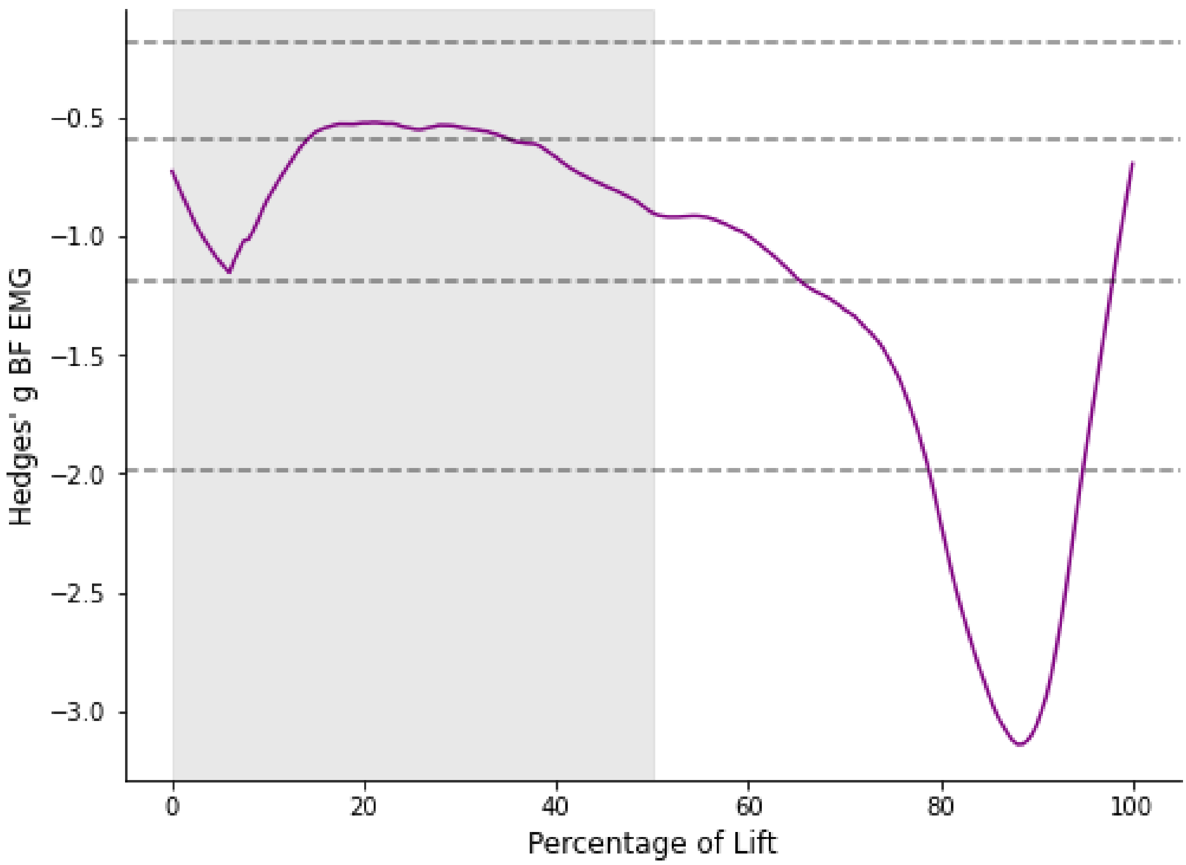
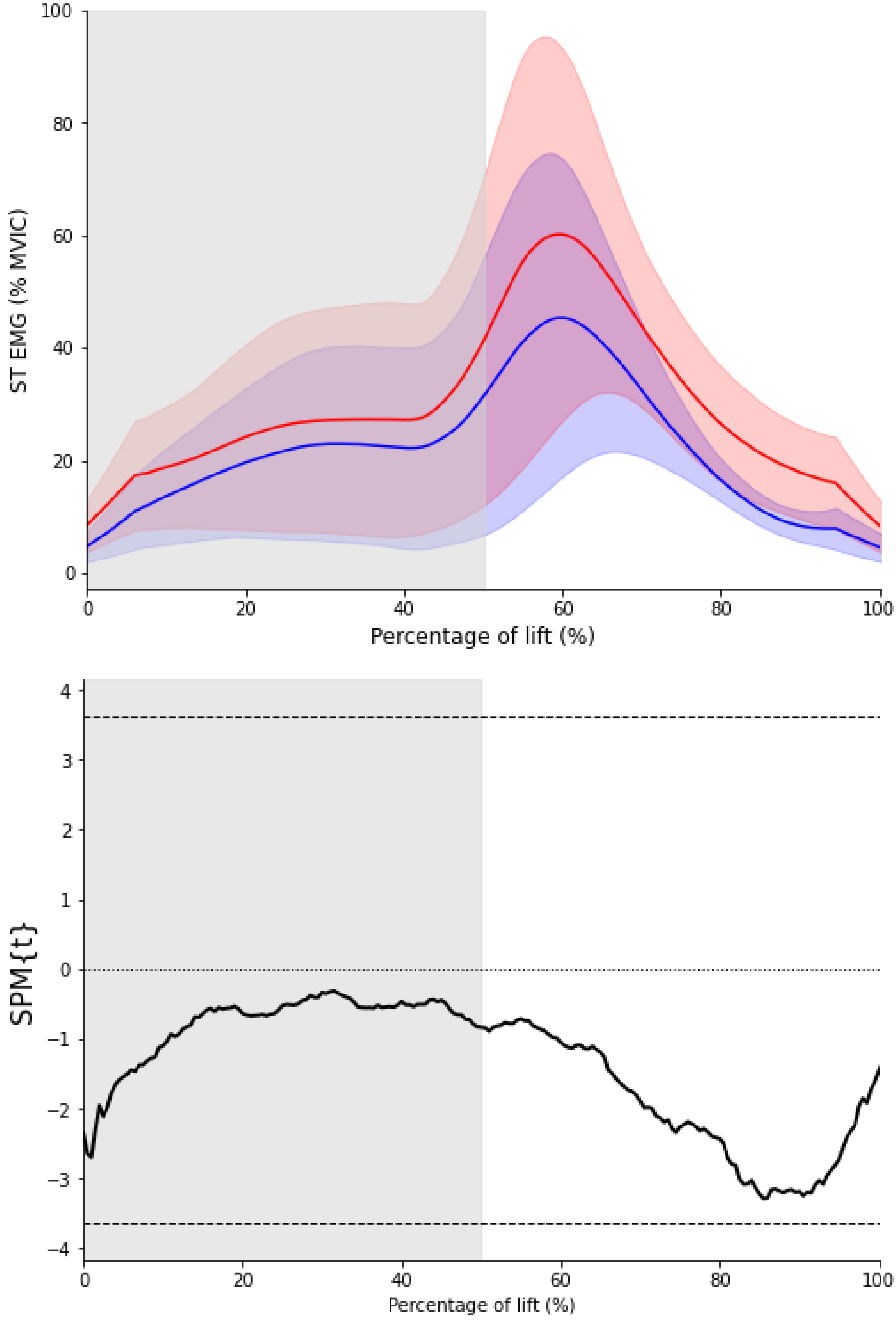


Figure 6-6 Time normalised BFLH muscle excitation (top) for the good morning (blue) and RDL (red).. Group means are represented by the solid lines with the upper the lower bound 95% CIs represented by the shaded areas. The t-statistic across normalised time (middle) is presented between the two lifts across normalised time. The Hedges g effect size is plotted across normalised time (bottom) with the horizontal dashed lines representing the thresholds of magnitude of effect. The grey shaded area between 0-50% on the X-axis of each plot shows the eccentric (lowering) portion of the lifts, with the white area between 50-100% of each plot representing the concentric (raising) portion of the lifts.

There was no significant difference in BFLH muscle excitation between the GM and RDL. However, the magnitude of difference in excitation was small-moderate in the eccentric phase of the lifts, but during the concentric phase of the lifts, the magnitude of difference increased to large-very large between 65-98% of normalised time, in favour of a higher level of excitation in the RDL.



ST EMG (% MVIC)
Percentage of lift (%)
SPM{t}
Percentage of lift (%)

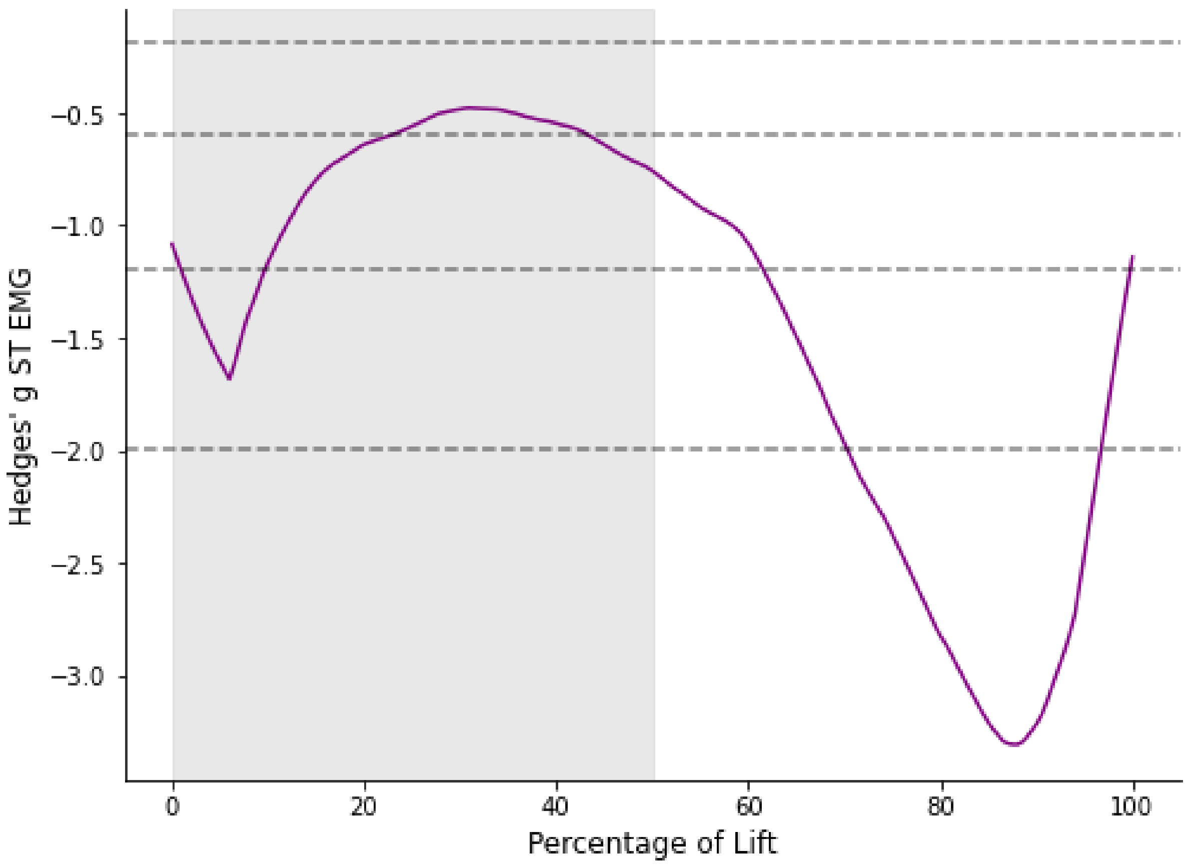
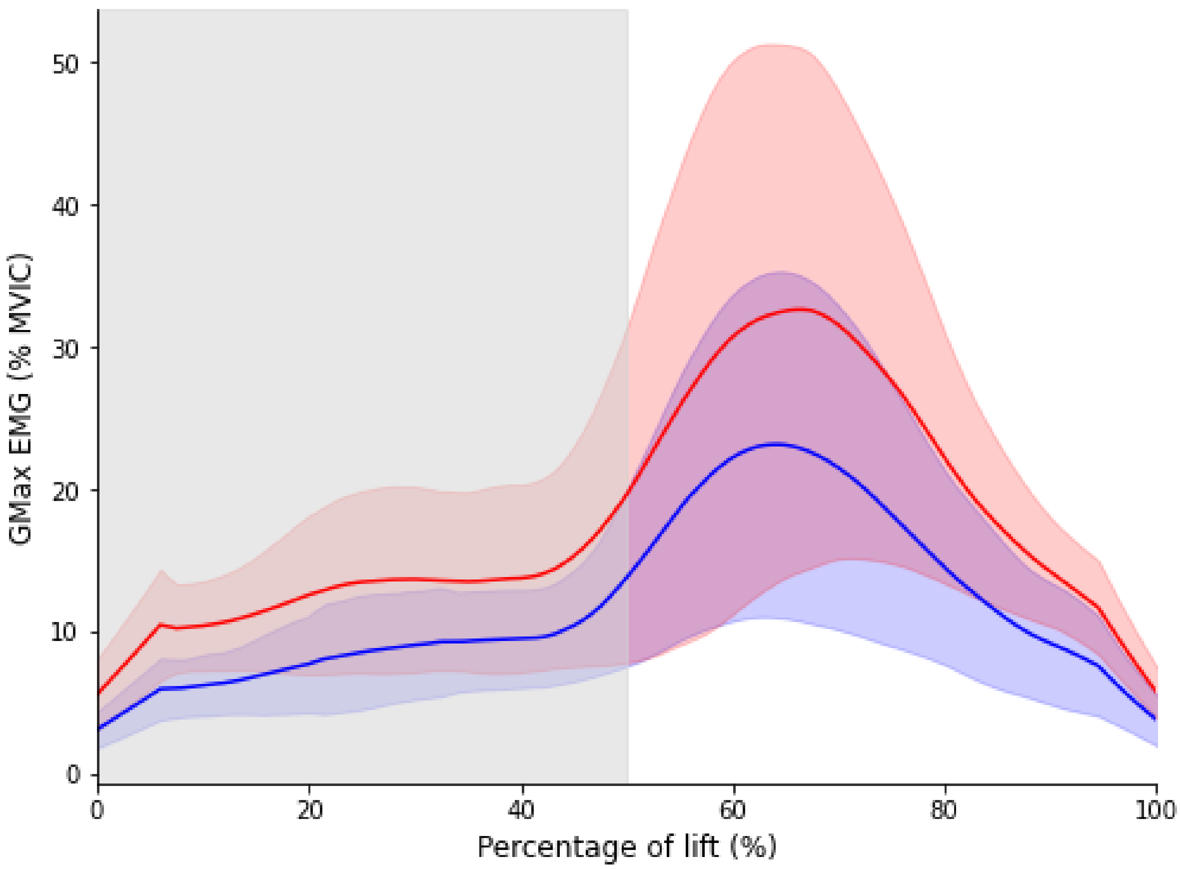
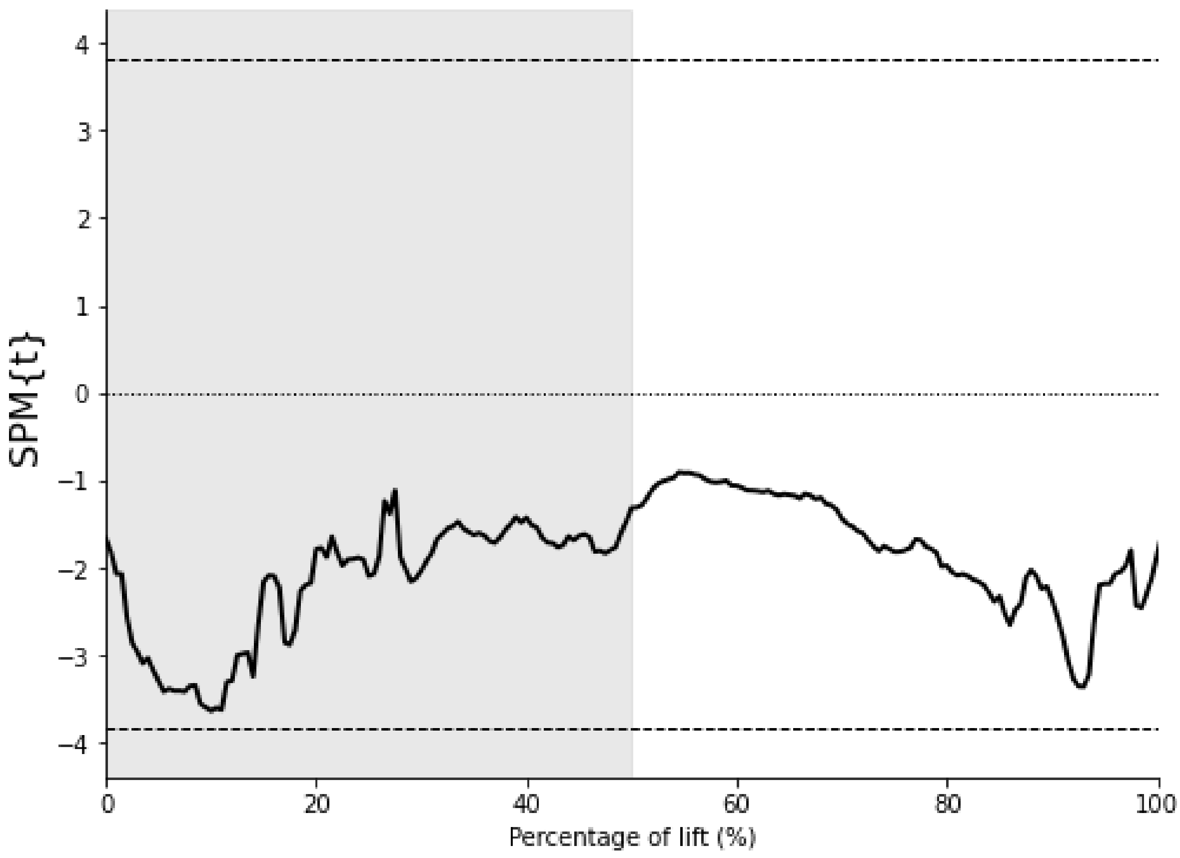


Figure 6-7 Time normalised ST muscle excitation (top) for the good morning (blue) and RDL (red). Group means are represented by the solid lines with the upper the lower bound 95% CIs represented by the shaded areas. The t-statistic across normalised time (middle) is presented between the two lifts across normalised time. The Hedges g effect size is plotted across normalised time (bottom) with the horizontal dashed lines representing the thresholds of magnitude of effect. The grey shaded area between 0-50% on the X-axis of each plot shows the eccentric (lowering) portion of the lifts, with the white area between 50-100% of each plot representing the concentric (raising) portion of the lifts.

There was no significant ($p \geq 0.05$) difference in ST muscle excitation between the RDL and GM. During the eccentric phase of the lifts, magnitude of difference in ST excitation ranged from small-large, however there was a steep increase in magnitude of difference from moderate to very large through the concentric phase of the lift, in favour of higher amplitude in the ST.



GMax EMG (% MVIC)
50
40
30
20
10
0
0
20
40
60
80
100
Percentage of lift (%)



SPM{t}
4
3
2
1
0
−1
−2
−3
−4
0
20
40
60
80
100
Percentage of lift (%)

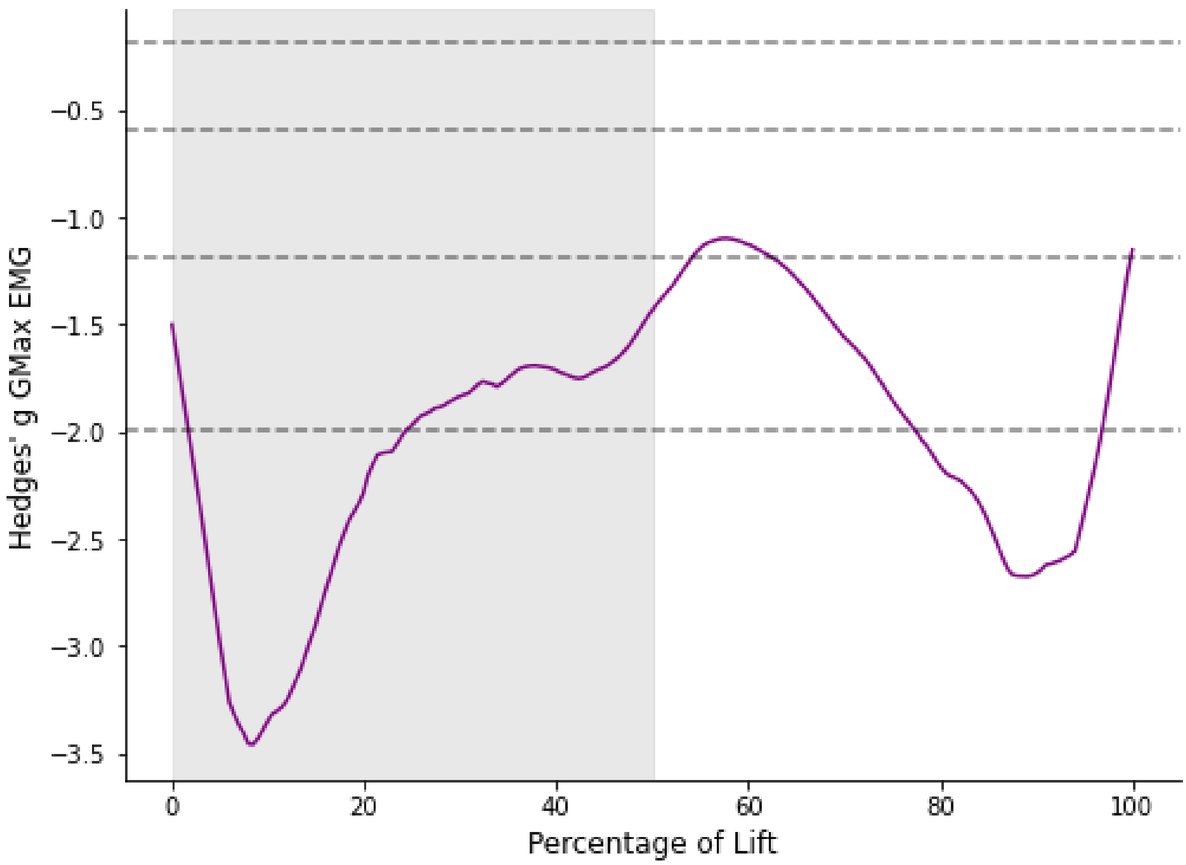


Figure 6-8 Time normalised GMax muscle excitation (top) for the good morning (blue) and RDL (red). Group means are represented by the solid lines with the upper the lower bound 95% CIs represented by the shaded areas. The t-statistic across normalised time (middle) is presented between the two lifts across normalised time. The Hedges g effect size is plotted across normalised time (bottom) with the horizontal dashed lines representing the thresholds of magnitude of effect. The grey shaded area between 0-50% on the X-axis of each plot shows the eccentric (lowering) portion of the lifts, with the white area between 50-100% of each plot representing the concentric (raising) portion of the lifts.

There was no significant difference sin GMax muscle excitation between the GM and RDL. During the eccentric phase of the lifts, the magnitude of difference in GMax excitation was large-very large in favour of higher excitation in the RDL. However, during the concentric phase, magnitude of difference ranged between moderate-very large.

6.6 Discussion

The aim of the current study was to compare hip and knee joint moments and hamstring and gluteal muscle excitation of two hip-hinge-based resistance training exercises, to better inform exercise selection decisions in strength and conditioning. The primary hypothesis of the study was partly accepted, as there were no significant differences in joint moments of muscle excitations between the two exercises, despite the higher absolute loads lifted during the RDL. The primary hypothesis was accepted in part, due to the presence of significant and very large differences in hip extensor moments between the two exercises in the first 7% (eccentric phase) and last 15% of the (concentric phase) lift. During these phases the GM exhibited lower hip extensor moments due to the decreased moment arm between the barbell centre of mass and the hip joint centre in the starting and finishing positions of the exercise. As a result, the findings of the current study indicate that while comparable levels of hip flexor and knee extensor moments and muscle excitations can be achieved under lower absolute loads during the GM compared with the RDL, the RDL is advocated as the exercise more likely to elicit greater adaptations in hip extensor strength due to the higher hip extensor moments, particularly in the final 15% of the movement.

In CHAPTER 4, it was found that even practitioners operating within elite-level sports often encounter challenges regarding equipment accessibility. Specifically, they noted a shortage of barbells and bumper plates, hindering their ability to conduct training sessions with higher absolute loads, especially when working with large groups of athletes. Additionally, some practitioners highlighted limitations of grip strength in their athlete groups when using the RDL. In such scenarios, the findings of the current study could prove valuable in guiding exercise selection for these sessions. The results of this study indicate that while higher hip extensor moments are achievable at the onset of the RDL compared to the GM, both lifts exhibit comparable moments and muscle excitations for the majority of the movement. These findings indicate that the GM could serve as an alternative hip-hinge-based exercise, requiring lower absolute loads yet potentially yielding similar training adaptations. However, it must be noted here that further research would be required to directly compare adaptations in strength between the two exercises using the same relative load, but higher absolute loads in the RDL.

To the author's knowledge, this is the first study to report joint kinetics during the GM exercise. On the other hand, comparable data on the joint kinetics of the RDL is limited, with only Lee et al. (2018) having reported ankle, knee and hip kinetics and muscle excitations of the RDL, and Van Hooren et al. (2022) reporting normalised muscle forces through musculoskeletal modelling during a single-leg RDL.

Lee et al. (2018) reported joint kinetics during the RDL performed at 70% 1 RM. Interestingly, Lee et al. reported higher peak knee flexor moments (0.21 Nm·kg·m) than those reported here (peak knee flexor moment 0.11 Nm·kg·m). In the study of Lee et al. (2018) the peak knee flexion angle was 32˚ whereas the peak knee flexion angle in the current study was 23˚. The lower knee flexor moment at a lower knee angle in the current study is surprising, given that a more flexed knee position would shorten the distal moment arm between the hamstrings and knee joint centre and create a shorter muscle-tendon unit. However, higher hip extensor moments with a higher degree of peak hip flexion were reported in the current study (peak hip extensor moment of 0.95 Nm·kg·m and 103° compared with Lee et al. (2018) (0.85 Nm·kg·m and 79˚). This would therefore lead to a larger forward displacement of the centre of mass, and a lengthening of the hamstring muscle tendon-unit due to the increased hip flexion, which may have kept the vertical ground reaction force vector closer to the knee joint centre in the current study than in that of Lee et al. (2018).

Several authors have reported muscle excitations during both the RDL (and variations including the stiff-leg deadlift) and the GM (Hegyi et al., 2019; McAllister et al., 2014 and Vigotsky et al., 2015), with considerable variability in findings. For instance, normalised peak muscle excitations in the BFLH have been reported between 12.0-98.6% MVIC and ranges of between 8.0-125.0% of MVIC reported in the MH (Bezerra et al., 2013; Bourne et al., 2017; Hegyi et al., 2018; Hegyi et al., 2019; Kawama et al., 2020; Lee et al., 2018; Lynn and Costigan, 2008; Malliaropoulos et al., 2015; Ono et al., 2010; Schoenfeld et al., 2015; Wright et al., 1999; Zebis et al., 2013). GMax excitations of 46.9% MVIC have been reported by Lee et al. (2018).

The muscle excitations previously reported in the literature are derived from a range of different loads, some of which are lower than the typical loads that would be used to elicit adaptations in maximal strength, such as the 12 RM loads used by Bourne et al. (2016). Additionally, the excitations reported in the existing literature are normalised using a range of different normalisation methods. Furthermore, some of the existing muscle excitations reported in the literature are expressed as values derived from the entire movement, rather than differentiating between the eccentric and concentric phases, with some authors also only reporting single time-point observations such as peak amplitude. Given that EMG amplitude is typically higher during concentric contractions than in eccentric muscle actions in load matched conditions, reporting only single time points or peak values does not provide the broader context of metabolic demand across each phase of a lift. Failure to differentiate between eccentric and concentric muscle actions may be problematic for between exercise comparisons. For instance, the NHE is typically eccentric only, therefore where authors (Zebis et al. 2013) have reported lower excitation in the NHE compared to other exercises that are not supramaximal in nature, these conclusions may have been largely influenced by differences in excitation due to contraction mode rather than due to exercise intensity. Reporting of mean amplitudes may mitigate the limitations of single time-point analyses (Burden et al. 2010) but again given that amplitude during the eccentric phase would be expected to be lower, there is still a need to differentiate between those phases.

The loads used in the current study (5 RM) provide an ecologically valid means of exercise comparison to inform potential impacts of exercise selection on the development of maximal muscle strength. Additionally, the amplitude normalisation method utilised has been shown to be reliable in both the BFLH and MH, based on early methodological work by the same author (CHAPTER 5; Ross et al. 2019). The findings of the current study indicate that there are no significant differences in muscle excitations during either the eccentric or concentric phases of the RDL or GM in the BFLH, MH or GMax.

McAllister et al. (2015) also investigated muscle excitations during the GM and RDL but used relative loads of 1 RM for each exercise. As expected, and as was in the case in the current study, participants in McAllister et al. (2015) lifted lower absolute loads in the GM than in the RDL (131.1 ± 43.3 kg and 172.0 ± 34.2 kg, respectively). As the load used in the current study would be the equivalent of 87.5% of 1 RM, when converting the loads used by McAllister et al. (2015), (87.5% of GM = 114 kg; 87.5% of RDL 150kg) it is clear that higher absolute loads were lifted in that study than in the current study. Therefore, while it should be acknowledged that the participants in the current study were relatively weak, both the current study and McAllister et al. (2015) no significant differences in either the MH or BFLH were reported. So, although it would be expected that overall magnitudes of joint moments and EMG amplitudes would be higher under heavier loads, it seems that the patterns of excitation or joint moments would be unlikely to be different between the two exercises. However, a direct comparison of muscle excitation amplitudes between the two studies is not possible as there was no amplitude normalisation used by McAllister et al. (2015). The participants used by Van Hooren et al. (2022) had a single leg RDL 5 RM (assuming 5 RM = 87.5% 1 RM) of 55.6 kg, however as it is not clear to what extent RDL repetition maximum is representative of single leg RDL performance, it is unknown if the assumed 1 RM RDL values in the current study (90.88 kg) indicate whether they were weaker than those in Van Hooren et al. (2022)

Strength training has been recommended as means of reducing risk of HSI. When considering specificity of training in relation to injury risk mitigation, exercises such as the NHE have been criticised for being ‘knee dominant’ exercises, when the common MOI for HSI incorporates simultaneous knee extension and hip flexion. As previously stated in the introduction to the current chapter, knee flexor and hip extensor moments have been reported at increasing running velocities. What is evident from the results of the current study is that the hip flexor and knee extensor moments experienced during both the GM and RDL at 5 RM loads are considerably lower than the moments experienced during high-speed running. For instance, the peak knee flexor moments reported here were 0.11 $Nm \cdot kg^{-1}$ and 0.14 $Nm \cdot kg^{-1}$ for the RDL and GM respectively, whereas Schache et al. (2011) reported knee flexor moments of 1.76 ± 0.28 $Nm \cdot kg^{-1}$ at 8.95 m·s. Peak hip extensor moments in the current study were 0.94 $Nm \cdot kg^{-1}$ and 0.86 $Nm \cdot kg^{-1}$ for the RDL and GM respectively, whereas Schache et al (2011) reported moments of 4.18 ± 1.26 $Nm \cdot kg^{-1}$ at 8.95 $m \cdot s^{-1}$. Therefore, it seems apparent that HSR is an important training intervention to ensure athlete exposure to appropriate specific loads that are not achieved through resistance training alone.

Currently empirical evidence in relation to the training methods that combine both resistance training and HSR training are very limited. Only Ripley et al. (2023) have reported adaptations to resistance training with either the addition of the NHE or sprint training on markers of HSI. Whereas Mendiguchia et al. (2020); Sancesse et al. (2023) and Freeman et al. (2019) have compared NHE training or sprint running training on running performance and / or knee flexor strength. While the study of Ripley et al. (2023) included the RDL in their training intervention, both the NHE and sprint groups in their study completed the RDL. As a result, it is difficult to establish the extent to which hip-hinge bias training programmes may affect HSI risk, with only Marchiori et al. (2022) directly comparing adaptations to RDL or NHE training, but without any HSR intervention, however the participants rugby players so presumably they did complete some HSR in their regular training, but this was not quantified.

Practitioners clearly value resisted hip-hinge actions and HSR as cornerstones of their training practices, even though the evidence-base around adaptations to such programmes is not as well established as adaptations to NHE training. Therefore, it is clear that more evidence is needed in relation to adaptations in concurrent resistance and HSR-based training and the potential benefits of training interventions that include a hip hinge bias compared with those that include a NHE bias.

6.7 Limitations

The primary limitation of comparisons of joint moments is that the individual muscle force contributions to said joint moments are not clear. Future research should aim to continue to develop knowledge and understanding of individual force contributions to resistance training exercises has been the case in Van Hooren et al. (2022) It should be noted, however that such estimations of muscle force contributions are computationally complex and require considerably more time and processing power than standard inverse dynamics analyses that were used here. Additionally, while a full critical analysis of musculoskeletal modelling methods is beyond the scope of the current study, many methods rely on knowledge of a muscle's maximal isometric force and physiological cross-sectional area. While data are available on maximal isometric forces of individual muscles, these are often based on cadaver specimens or animal models and therefore may not be reflective of trained human participants. Challenges also exist in terms of estimations of physiological cross-sectional area of a muscle given that these would either require costly magnetic resonance imaging or are derived again from cadavers.

6.8. Conclusion

The results of the current study indicate that comparable knee and hip joint moments and muscle excitations can be achieved throughout the majority of both the RDL and the GM exercises. However, significant and very large increases in hip extensor moments can be observed during the first 7% and last 15% of the RDL comparted to the GM. This finding, coupled with the ability to lift higher absolute loads in the RDL is indicative of potentially greater adaptations in maximal strength from the RDL compared with the GM. However, in situations where the RDL may be impractical such as a lack of access to sufficient bumper plates, when upper limb injury may limit grip strength in the RDL, the GM may likely serve as a suitable alternative.

As identified in CHAPTERS 3 and 4, there is a need for more empirical evidence in relation to adaptations to training from ecologically valid training programmes which include the hip hinge. CHAPTERS 5 and 6 aimed to develop a more robust exercise selection rationale for hip-hinge based exercises beyond EMG-based exercise selection alone. As the results from the current study indicated that the RDL and GM were comparable in terms of joint kinetics, kinematics and muscle excitation, it was decided that the RDL would be utilised in the training intervention study presented in CHAPTER 8. It was also planned that the NordBord would be used in CHAPTER 8 as a means of assessing adaptations in knee flexor strength. However, given that the majority of existing studies in relation to the NordBord, are restricted to measurements of peak force alone, a more detailed analysis of the force-time characteristics was warranted. Further to this, authors often refer to the study of Opar et al. (2013) to demonstrate the acceptable levels of reliability of the NordBord, however the prototype model utilised by Opar et al. (2013) had a higher sample frequency than the commercially available model and therefore reliability of the commercially available device has yet to be established.

Chapter 7 The Reliability and Comparison of Force Characteristics During the Nordic Hamstring Exercise

7.1 Chapter Overview

The chapter covers the primary data collection and analysis procedures in order to quantify knee flexor strength and assessment of bilateral force asymmetry. The chapter also presents data in relation to the magnitude and direction of between-limb asymmetries during the Nordic hamstring exercise. The results of the pilot study are then interpreted and discussed in detail to inform the methods included in the future exercise comparison and training intervention study presented within this thesis.

7.2 Introduction

The NHE is effective at increasing knee flexor eccentric strength, (Presland et al., 2017b) which can help to mitigate hamstring strain injury occurrence.(Al Attar et al., 2017; Rey et al., 2017; Ribeiro-Alvares et al., 2018; Severo-Silveira et al., 2018; van der Horst et al., 2015; van Dyk et al., 2019; Whyte et al., 2019) A portable device called the 'NordBord' has been developed to assess the forces produced by both the left and right limbs during the NHE to help evaluate, and subsequently monitor changes in, knee flexor eccentric "strength" (Opar et al., 2013) The test-retest reliability of both the between-trial peak force (PF, the highest force produced across trials) and between-trial mean PF (the average PF produced across trials) during the NHE, as measured by an initial NordBord prototype, was reported as acceptable (intraclass correlation coefficient [ICC] = 0.83-0.90; coefficient of variation percentage [CV%] = 5.8-11.0%), (Opar et al., 2013) but the prototype had a higher sample frequency than the current production version that is now widely used in sport (1000 vs 50 Hz, respectively). This an important factor as the force-time sample frequency of the NordBord may influence the reliability of resultant force-time variables of the NHE. This has been shown for common tests conducted on a force platform, such as the countermovement jump, (Hori et al., 2009) however force-time sample frequency during isometric mid-thigh pull, has been shown to have trivial and non-significant influence on PF and rate of force development measures. (Dos'Santos et al., 2019) Thus, determining the reliability of NHE force-time variables calculated using the production version of the NordBord is warranted. Additionally, the between-trial reliability of PF produced during the NHE along with the between-trial mean force (MF) obtained between the onset of movement and PF (i.e. the MF calculated within a trial rather than the average PF produced across trials) is currently unreported and, thus, warrants further exploration.

Bilateral force asymmetries of ≥15% and ≥20% have been cited as risk factors for future HSI in rugby union players (Bourne et al., 2015), but not in Australian Rules football players. (Opar et al., 2015) A reduction in bilateral force asymmetries during the NHE, has been reported to reduce HSI incidence, (Croisier et al., 2008; Fousekis et al., 2010) however, only with respect to between-trial PF and mean PF (average peak force across 2 sets of 3 NHE repetitions) (Opar et al., 2013). The PF values alone describe just one force data point in a complete force-time series; thus, they do not describe how force differs or changes between limbs throughout the full NHE. As mentioned earlier, the between-trial PF and mean PF also do not inform how PF and MF changes during the NHE from trial to trial. Comparing the relative force contribution from each limb *during* (i.e. instantaneous force [IF]) the full performance of the NHE (i.e. throughout the entire range of motion) between-trials may inform likely strength adaptations to be experienced by each limb after completing the NHE as part of a strength training program (i.e. if one limb is contributing more [from a force perspective] to the bilateral NHE), in addition to potential HSI risk factors.

7.3 Aims and Hypotheses

The purpose of this study was twofold: firstly, the study aimed to ascertain the between-trial reliability of PF and MF during the NHE performed on the NordBord. Secondly, to calculate bilateral differences in PF, MF and IF throughout the NHE performed on the NordBord, normalized to 100% of the movement (i.e. from onset of movement through to PF). It was hypothesised that MF and PF would be lower during the first repetition than in subsequent repetitions, due to potential positive learning effects, which have also been reported in other force-time analyses such as during the countermovement jump (Markovic et al., 2004) and that significant differences in IF would be evident between limbs.

7.4 Methods

7.4.1 Participants

Nineteen strength-trained male subjects (age 30.6 ± 8.1 years, body mass 84.4 ± 5.9 kg, height 1.79 ± 0.06 m), who were experienced in performing the NHE, volunteered to participate in this study. Written informed consent was provided prior to testing.

7.4.2 Research Design

This study employed the use of a cross-sectional research design, whereby PF, MF and IF were determined during the Nordic hamstring exercise, performed on the NordBord. Subjects attended a single testing session in a laboratory setting, having refrained from exercise for ≥48 hours.

7.4.3 Data Collection

Following a warm-up, participants performed three maximal NHE trials, interspersed by one minute, on a NordBord (Vald Performance, Newstead, Australia), sampling force data at 50 Hz. The NHE technique was performed as previously described, (Opar et al., 2013) however briefly; the NHE was performed with the participant starting in a kneeling position with the knees on the padded surface of the NordBord. The ankles were secured in position by individual braces, attached to uniaxial load cells. The ankle braces were positioned perpendicular to the shank for testing to ensure that all force generated by the knee flexors was applied and recorded purely along the long axis of the load cell, once the ankles were positioned appropriately. Once in position, participants were instructed to place their hands out in front of their torso, with the shoulders in a neutral position, elbows flexed to approximately 90˚ to allow the use of the hands to cushion their descent at the end of the movement. To complete the NHE participants were instructed to learn forward as slowly as possible while maintaining a neutral (0˚ extension) hip position and an upright trunk, while maximally resisting this movement using the knee flexors of both limbs, until unable to continue to resist knee extension, or until the movement was completed by reaching approximately 0˚ knee extension. In Microsoft Excel, the average (mean) force plus five times the standard deviation (±) was calculated from the initial second of data which corresponded to when participants were knelt upright (i.e. knees, hips and upper body in vertical alignment) before they commenced the NHE. This calculation created a 'force threshold', with the onset of movement defined as the instant at which force exceeded this value. The PF was defined as the highest force after the onset of movement. The MF was calculated as the average force between the onset of movement and PF. The PF was used as a reference point for the end of the NHE trial because this instant was assumed to be immediately proceeded by falling to the ground (i.e. when participants were no longer able to resist knee extension) and is illustrated by a clear and rapid decrease in force.

7.4.4 Statistical Analyses

Relative reliability was determined using ICC (3,1) and associated 95% confidence intervals (CI), with values of <0.5, between 0.5 and 0.75, between 0.75 and 0.9 and >0.9 were considered poor, moderate, good and excellent, respectively, based on the lower bound CI. (Koo and Li, 2016) Absolute variability was calculated using CV%, with ≤10% considered acceptable. Likely limb differences in IF (between onset of movement and PF) were determined by plotting the time normalized (200 samples) ensemble average curves for each limb with upper and lower 95% confidence intervals and identifying non-overlapping areas. All variables were tested for normality using the Shapiro-Wilk test and all observed values were normally distributed. Mean differences (α = 0.05) in PF and MF between trials were identified using a repeated-measures analysis of variance with Bonferroni post-hoc analysis between individual trials. Within trial differences between the left and right limbs were compared using dependent t-tests. Magnitude and direction of between-limb asymmetry (%) for each individual participant trial was calculated, as per Shorter et al. (Bishop et al., 2020; Shorter et al., 2007). Negative asymmetry values represent an asymmetry favouring the right limb. Effect size calculations (Cohen's *d*) were performed to provide a measure of the magnitude of the mean differences in PF and MF between trials and limbs and was interpreted using the following scale: *trivial* ≤0.19; *small* 0.20 – 0.59; *moderate* 0.60 – 1.19; *large* 1.20 – 1.99; *very large* ≥2.00. All statistical analyses were performed using SPSS software (version 23; SPSS Inc., Chicago, IL, USA).

7.5 Results

PF increased subtly across trials (Figure 7-1), with trivial-small but non-significant differences noted between trial 1 and trials 2-3 (*d* = 0.15-0.29; *p* = 0.125 – 0.459) but only trivial differences noted between trials 2 and 3 (*d* = 0.10-0.13; *p* = 0.958 - 1.00). MF increased across trials with trivial-small differences noted between trial 1 and trials 2-3 (*d* = 0.004 - 0.44; *p* = 0.038 – 0.271). Post-hoc analysis showed that MF was higher in trial 3 than trial 1 in the left limb (*d = 0.29; p* = 0.021). Reliability and variability of PF between trials 1, 2 and 3 was moderate to excellent and acceptable, respectively (ICC = 0.823-0.834 95% CI = 0.666 – 0.926, CV = 9.0-9.1%) but this was not evident for MF (ICC = 0.651-0.690, 95% CI = 0.413 – 0.835, CV = 12.6-13.8%). Reliability and variability of both PF and MF, between trials 2 and 3, however, were moderate to excellent and acceptable (ICC = 0.835-0.875, 95% CI = 0.627 – 0.950, CV = 7.0-9.9%), respectively.

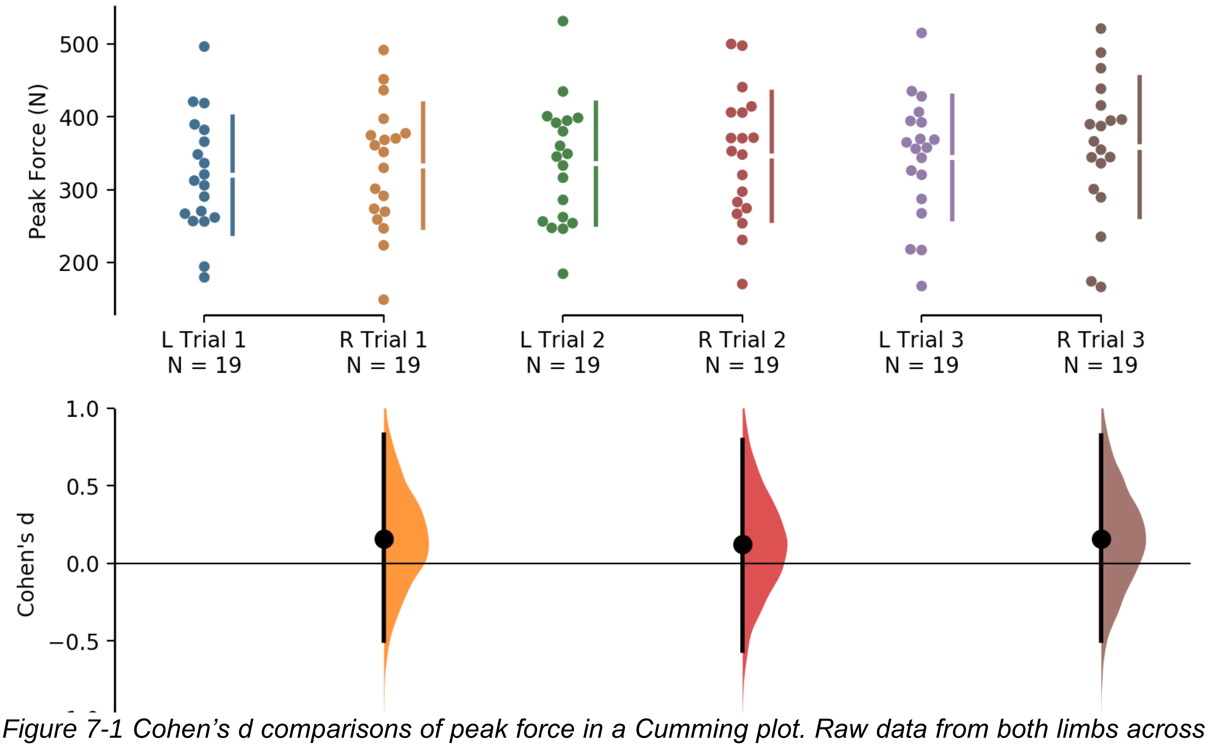


Figure 7-1 Cohen's d comparisons of peak force in a Cumming plot. Raw data from both limbs across each trial are presented on the upper axes; each mean difference is plotted on the lower axes as a bootstrap sampling distribution. Mean differences are depicted as dots; 95% confidence intervals are indicted by the ends of the vertical error bars.

Between limb measures of PF were trivial, non-significant (*d* = 0.16; *p* = 0.071) (left = 333.1 ± 78.5 N; right = 345.9 ± 84.7 N) but there was a small, significant (*d* = 0.34; *p* = 0.005) difference in MF (left = 179.6 ± 45.0 N; right = 195.8 ± 49.5 N) between limbs. Additionally, IF was higher for the right limb between 10 and 89% of normalised time (FIGURE 7-3).

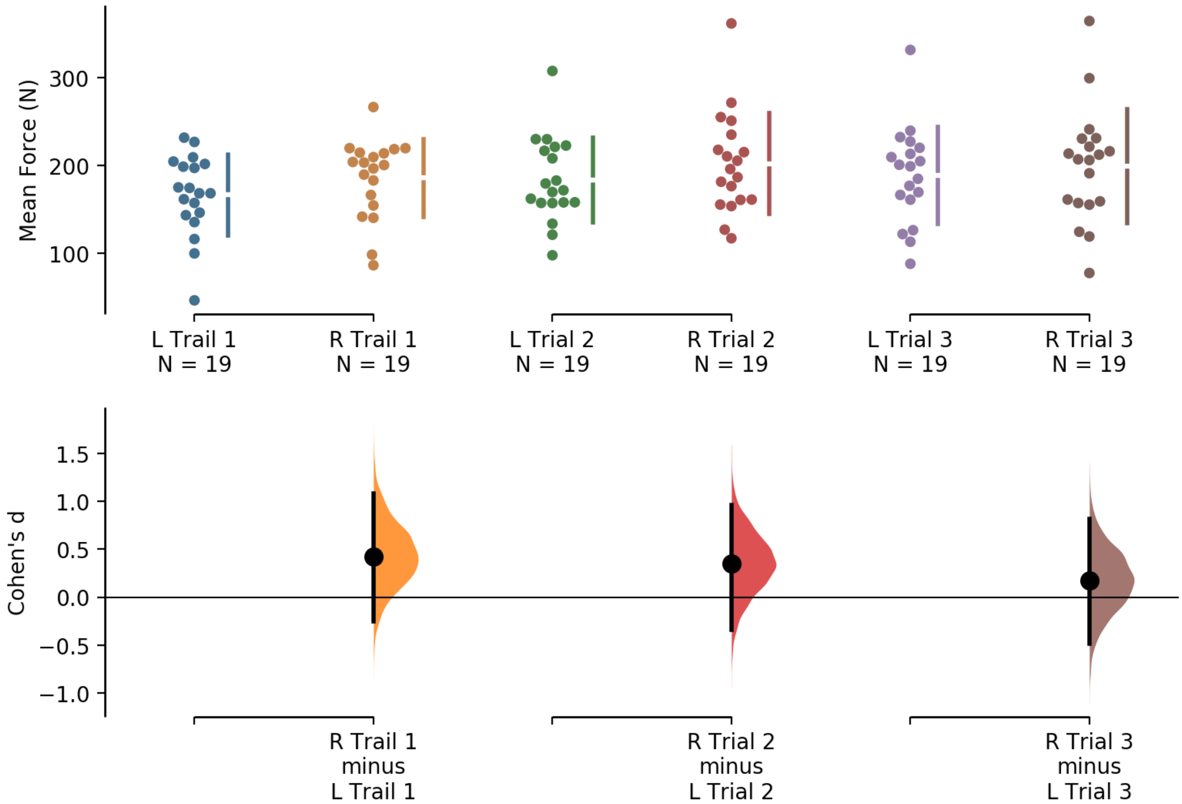


Figure 7-2 Cohen's d comparisons of mean force in a Cumming plot. Raw data from both limbs across each trial are presented on the upper axes; each mean difference is plotted on the lower axes as a bootstrap sampling distribution. Mean differences are depicted as dots; 95% confidence intervals are indicted by the ends of the vertical error bars.

When only considering trials 2 and 3, between limb measures of PF were trivial, non-significant (*d* = 0.14; *p* = 0.47) trivial (left 339.8 ± 84.1 N; right 352.4 ± 92.1 N) but there was a small significant (*d* = 0.26; *p* = 0.005) difference in MF (left 186.2 ± 51.7

N; right 200.8 ± 61.2 N). There were no significant within trial differences in MF or PF between limbs.

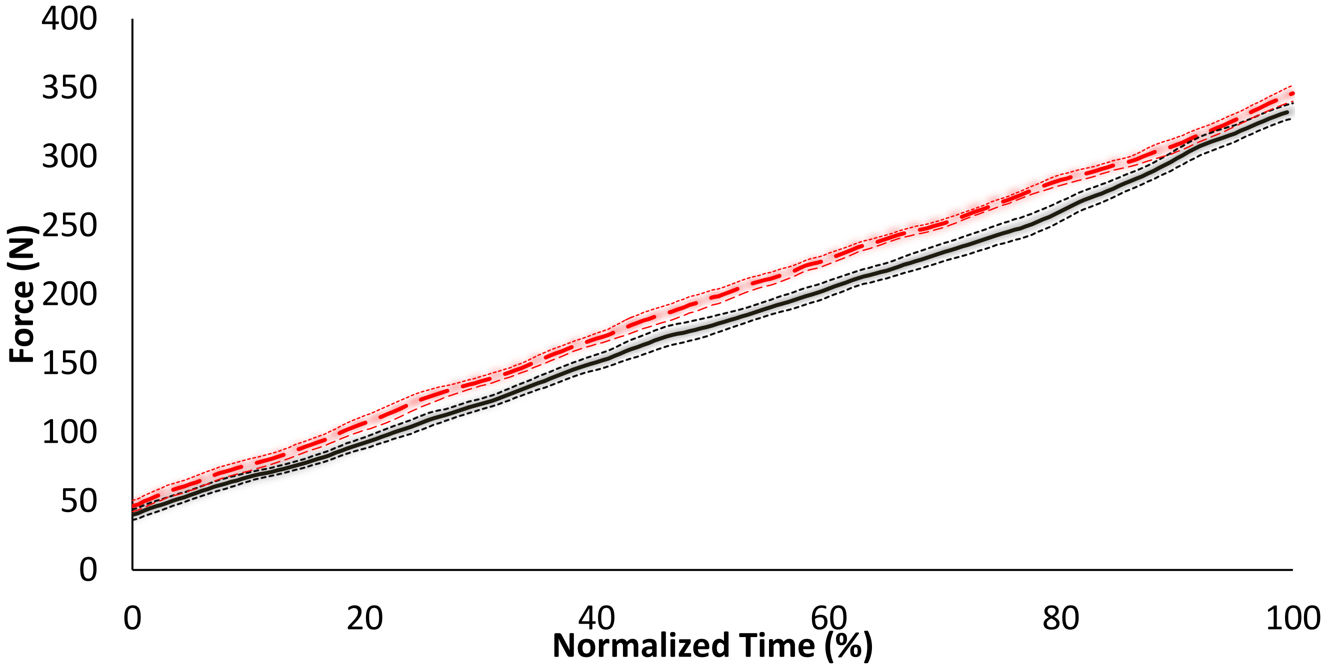


Figure 7-3 Mean force-time curves normalized to 100% of the movement (onset threshold through to peak force) across all three trials. Left leg mean is represented by the solid line and long-dashed line represents right limb mean the mean with shaded areas representing 95% CI. Statistically significant differences between the right and left limbs are represented by the areas at which the 95% do not overlap i.e. between 10-89% of normalized time.

The direction of between-limb percentage asymmetry is presented in FIGURE 7-5 for PF and MF, respectively. Individual PF asymmetry values ranged from 0.4 to 13% for PF and 0.1 to 60.7% for MF. However, with the outlier of trial one from participant 12 removed, this MF range is adjusted to 0.1 to 26.5%. The direction of asymmetry was variable for some, but not all participants. With regards to PF, five participants demonstrated instances in which the direction of PF force asymmetry was inconsistent between limbs. With regards to MF, seven participants demonstrated such directional asymmetry inconsistencies.

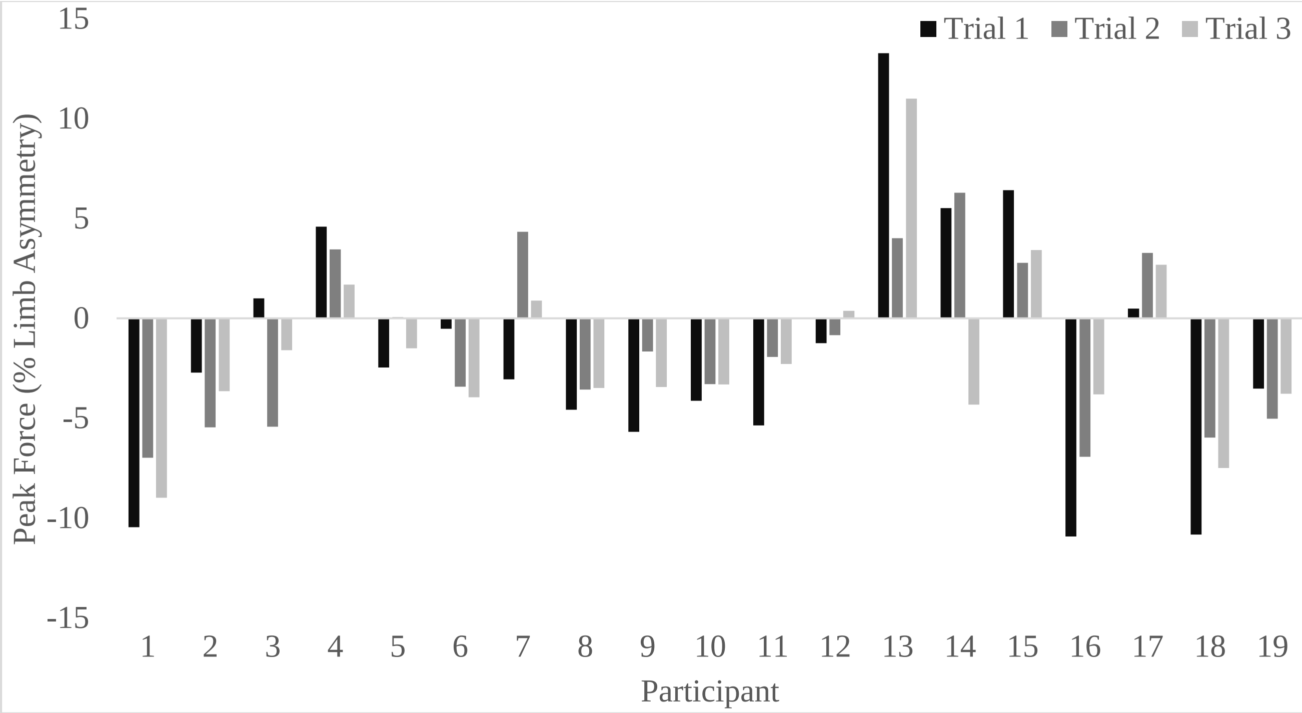


Figure 7-4 Peak force percentage limb asymmetry for all participants across trials. Negative asymmetry values represent an asymmetry favouring the right limb.

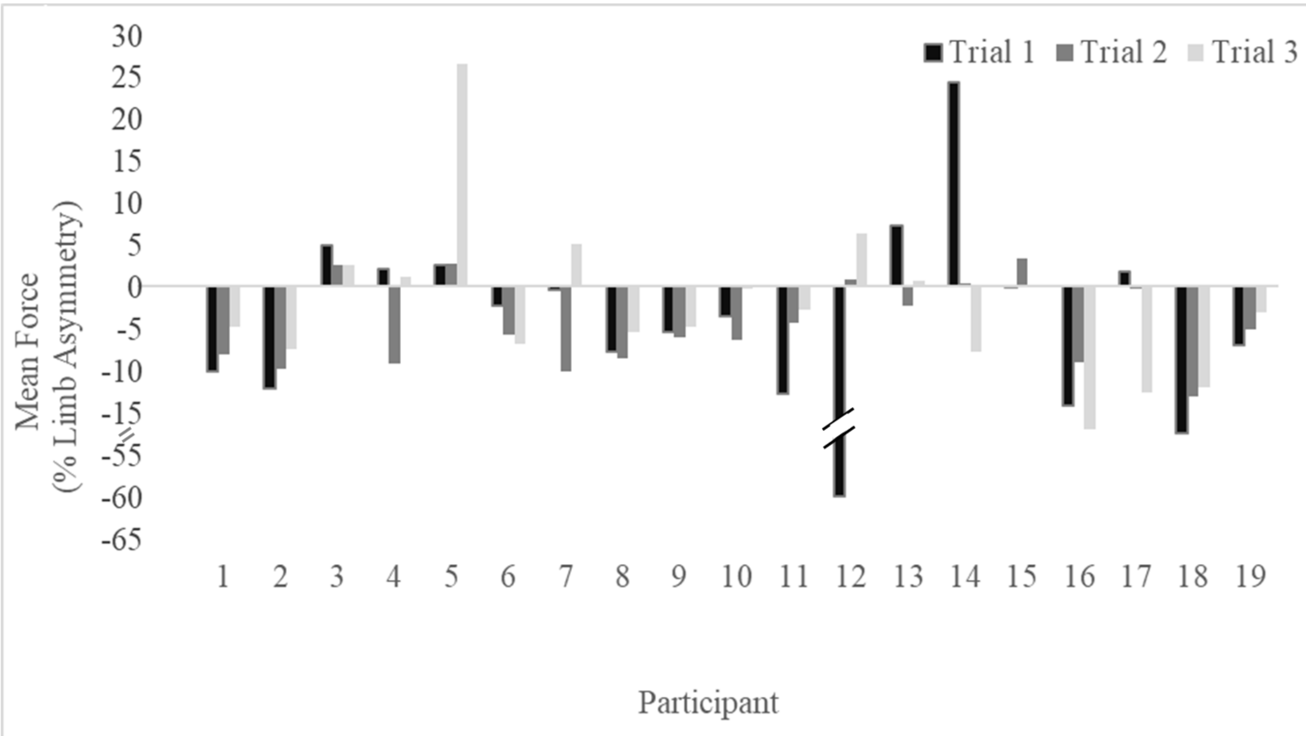


Figure 7-5 Mean force percentage limb asymmetry for all participants across trials. Negative asymmetry values represent an asymmetry favouring the right limb.

7.6 Discussion

The purpose of the current study was to establish between-trial reliability of PF and MF scores obtained on the commercially available version of the NordBord, at a sample frequency of 50 Hz. Additionally, the study aimed to calculate bilateral differences in PF, MF and IF during the NHE. The assessment of IF, was of interest, given that only the PF scores are reported in the majority of existing NHE studies, (Bourne et al., 2019; Chalker et al., 2016; Chalker et al., 2018; Markovic et al., 2018; Opar et al., 2015; Timmins et al., 2015; Timmins et al., 2016; van Dyk et al., 2018) only providing one force data point across the entire time-series during the exercise and therefore may not provide a detailed overview of potential training adaptations. Minimal learning effects were observed between the three trials of the NHE (subtle trial-trial increase in PF and small-significant significant-small increase MF)., and both reliability and variability were improved, when the final two trials alone were compared. It may be prudent, therefore, to discard the first of multiple maximal NHE trials performed on the NordBord to account for this learning effect and reduce the likelihood of underestimating true PF and MF scores.

A further observation made within the present study, is that regardless of whether all trials, or only trials 2-3 were considered, MF was statistically higher in the right limb, albeit small in magnitude. The between-limb difference in MF seems to highlight the importance of practitioners including MF in the athlete assessment, given that the NHE is often used as a rehabilitative or injury prevention technique for HSI. Should one limb produce greater MF over normalised time, it would be expected that the stronger limb would experience greater strength training adaptations due greater training load over normalized time. This may reduce the effectiveness of the NHE for reducing HSI risk in the weaker limb, as it undergoes a reduced training impulse, which can be supported by the findings of Hegyi et al. (2019) that compared bilateral and unilateral NHE variations on an alternative device and found significantly greater knee flexor torque in the bilateral NHE, compared with a single leg variation (in 0˚ hip extension), however no statistically significant differences were reported between the bilateral and unilateral variations of the NHE when the hip was flexed to 90˚.

The results of this study indicate that monitoring PF asymmetries alone during the NHE masks the magnitude and nature of knee flexor force asymmetries before PF is achieved. This can be evidenced by the non-significant trivial between limb differences in PF reported here, while significant-small differences were evident in MF and higher IF in the right limb between 10 and 89% of normalised time. It may be prudent, therefore, for researchers and practitioners who use the NordBord to analyse MF and IF, alongside PF, for each limb when determining bilateral asymmetries during the NHE, particularly in those athlete groups that may already be at risk of between-limb strength asymmetries due to the nature of their sport (e.g. sports with a particularly dominant limb). None of the participants in the current study demonstrated PF asymmetry values of ≥15%, which has previously been reported as risk factor for HSI. (Bourne et al., 2015) A key reason for this may be that the asymmetry calculation used by Bourne et al. (2015) originally proposed by Impellizzeri et al. (2008) is arguably better suited to unilateral tasks, rather than in the bilateral NHE. For a more in-depth discussion around selection and interpretation of asymmetry calculations, see Bishop et al. (Bishop et al., 2020) Figure 7-4 indicates that the direction of asymmetry can be highly variable, in agreement with research from Bishop et al. (2020) Additionally, while between-limb measures of MF were found to be small-significant, also indicates the highly variable direction of asymmetry. While the influence of MF asymmetry derived from the NHE as a HSI risk factor has yet to be explored, the findings of the current study are in agreement with Bishop et al. (2020) that a means analysis approach to PF and MF asymmetry may be inadequate and may require an individualised approach. However, even at an individual level, the variability of such asymmetry analyses leads to questions over the usability of asymmetry as a meaningful indicator of HSI risk.

Previous studies have suggested that real-time feedback can lead to significant acute and chronic increases in muscle strength. (Keller et al., 2014; Randell et al., 2011) The NordBord software, provides clear, real-time force-time traces which can be used to provide such feedback to participants during the NHE. Chalker et al. (2018) reported that the use of such feedback increased mean PF, compared to no additional visual feedback, largely in the weaker of the two limbs. Future studies may also consider the effects of augmented feedback on between-trial reliability of PF and MF, however the findings of Chalker et al. (2018) suggest that augmented feedback is ineffective at reducing between limb asymmetries. Therefore, should an athlete demonstrate significantly lower MF and/or IF in one limb (such as during HSI injury rehabilitation), then the practitioner may consider implementing additional unilateral exercises, however this may warrant further investigation given that some, (Anastasi & Hamzeh, 2011) but not all training intervention studies have reported that bilateral NHE can reduce between limb knee flexor asymmetries (Whyte et al., 2019).

7.7 Conclusion

The results of the current study indicate a potential learning effect from performance of the NHE, observed through the analysis of MF. The reliability and variability of MF measures can be improved by excluding the first of multiple trials of the NHE. The use of PF analysis alone may mask the effect of between-limb force asymmetry given that there was only trivial, non-significant between-limb differences in PF. However, analysis of IF demonstrated that force was higher in the right limb between 10-89% of the movement, indicating that the right leg experiences significantly greater training impulse throughout the movement, which was also observed through a small, but significant difference in MF favouring the right limb across trials. However, the study also indicates that the magnitude and direction of between-limb force asymmetries may not be consistent across trials and should therefore be analysed on an individual participant basis, prior to making any assertions on HSI injury risk, based on between-limb force asymmetry.

The current findings of the current chapter indicate that the commercially available NordBord is a reliable means of assessing knee flexor strength, but that reliability can be improved by removing the first of multiple repetitions performed. As a result, it was decided that when assessing knee flexor strength in CHAPTER 8, participants would complete four repetitions, with the first repetition being excluded from the analysis to promote reliability and negate the impact of the potential learning effect on strength measures.

Chapter 8 Integration of a knee flexor bias or hip hinge bias resistance training programme with combined high-speed running in academy soccer players

8.1 Chapter Overview

This chapter covers issues around ecological validity of the majority of hamstring specific training interventions aimed at mitigating risk of HSI and enhancing athletic performance (e.g., sprint running and jump performance). Adaptations to two ecologically valid (and a control) training interventions, which were informed by the qualitative data presented in CHAPTERS 3 and 4 are presented. Adaptations are quantified across a range of measures relating to injury risk and athletic performance, including maximal knee flexor strength, isometric mid-thigh pull, countermovement and countermovement-rebound jumps, and maximal sprint performance. The results of the training interventions are then critically discussed to inform applied practice in the implementation of ecologically valid training programmes and the potential adaptations that can be expected.

8.2 Introduction

Currently, the majority of literature relating to the mitigation of HSI risk factors is focused on the use of single exercise training interventions such as the eccentric only NHE (Alt et al., 2017; Clark et al., 2005; Delahunt et al., 2016; Anastasi and Hamzeh, 2011; Iga et al., 2012) or eccentric vs concentric (Mjølsnes et al., 2004; Timmins et al., 2016) training methods. While the results of such investigations provide valuable insight into the potential effects of training on HSI risk, there is a lack of ecological validity given that it is highly unlikely that applied practitioners would use single interventions. Previously, Bahr et al. (2015) reported that evidence-based NHE protocols were poorly adopted in elite-level European soccer. However, it must be highlighted here that Bahr et al. (2015) surveyed practitioners on how they adopted a specific NHE protocol which progressed to very high weekly volumes (90 repetitions). Ripley et al. (2021) has highlighted that adherence to NHE programmes is likely a key determinant of the success of a programmme in injury risk mitigation. Furthermore, the systematic review and meta-analysis of Cuthbert et al. (2020) has highlighted that there seems to be no additional benefit of high-volume NHE programmes over low-volume programmes, which may create scope for practitioners to enhance adherence by utilising low-volume training programmes.

In CHAPTERS 3-4 it was found that the majority of practitioners that responded to the survey and took part in interviews indicated that while training for the mitigation of HSIs was certainly a goal of their strength and conditioning practices, it was generally a training goal that was addressed alongside other aims such as the desire to develop athletic potential (e.g., maximal sprint and jumping ability) and general strength. Therefore, an investigation into the effects of combined resistance and HSR training on HSI risk and athletic performance is warranted.

Previously, researchers have quantified the effects of eccentrically biased resistance training (primarily through the NHE) on knee flexor strength. While the methods used such as training intervention, participant cohorts and methods used to measure adaptation vary across the literature, generally there is a trend towards a likely beneficial effect of the NHE on knee flexor strength. In a systematic review and meta-analysis, Cuthbert et al. (2020) indicated that the studies of Alt et al. (2017); Clark et al. (2005) and Delahunt et al. (2016) yielded only trivial effects from their training interventions. The reasons for the trivial effects reported in Alt et al. (2017) may be that the training intervention was only four-weeks in duration which may not have been sufficient to elicit larger increases in knee flexor strength (Ripley et al., 2021). However, it must also be noted that six of the 12 training sessions in the study of Alt et al. (2017) were performed using an assistance cable, potentially reducing the resulting force, to control angular velocity of the knee joint during the NHE. Controlling the knee joint angular velocity may have helped to better control time under tension during the NHE, it also would cause a reduction in exercise intensity by allowing the cable to support some of the participant's body weight. Clark et al. (2005) used a small sample (*n* = 9) of relatively weak participants (baseline peak eccentric knee flexor torques of 98.61 - 99.00 Nm), that performed partner assisted NHEs during the programme. Unfortunately, the angular velocities, or range of motion performed during training repetitions was not monitored. Given that the participants were relatively weak at baseline, it can be speculated that they may not have had sufficient levels of strength to maintain a controlled NHE descent through to near full knee extension which may have limited the adaptation to the stimulus. Delahunt et al. (2016) utilised the same high volume (progressing to 90 weekly repetitions) NHE programme that Bahr et al. (2015) previously surveyed in elite level European soccer, which given the supramaximal nature of the NHE exercise it would seem plausible that sets of twelve, ten and eight repetitions would likely lead to a reduction of repetition intensity due to the accumulation of intra-set neuromuscular fatigue, which may have led to the trivial magnitude of response.

In contrast, several researchers reported beneficial effects of NHE training ranging from small to very large in relative eccentric peak torque (Anatasi and Hamzeh, 2011; Iga et al., 2012; Ribeiro-Alvares et al., 2017; Seymore et al., 2017; Tansel et al., 2008) eccentric peak torque (Mjølsnes et al., 2004) and eccentric force (Freeman et al., 2019; Ishoi et al., 2018 and Presland et al., 2018) Furthermore, Cuthbert et al. (2020) also indicated that there seems to be no additional benefit of higher volume NHE training over lower volumes. The two studies with the most contrasting weekly volumes

(440 *versus* 128 total repetitions) in the meta-analysis of Cuthbert et al. (2020) Mjølsnes et al. (2004) and Presland et al. (2018), both interestingly reported the two largest positive effect sizes from all of those included in the analysis. Muscle soreness has previously been cited as a limiting factor for compliance to NHE training programmes (Bahr et al., 2015; Behan et al., 2023). As a result, limited compliance may hinder potential adaptations to the training stimulus. (Ripley et al., 2021)

From CHAPTER 4 it seems apparent that applied practitioners are largely adopting the recommendations that lower volumes of NHEs can be sufficient to elicit positive adaptations in hamstring strength with practitioners programming an average of 17 weekly NHE repetitions during the off-season, reducing to an average of twelve weekly NHE repetitions during the in-season. More recently, Cadu et al. (2022) reported improvements in maximal eccentric knee flexor strength from even lower volumes of the NHE (1x3 repetitions) over a 21-week period, with those classified as high compliance (~13 days between sessions) experiencing significant-large ($p \leq 0.01$; $g = 1.20$) improvements in eccentric strength comparted with a low compliance (~24 days between sessions) group, which seems to lend further support to the potential benefits of low volume NHE training. Additionally, Cadu et al. (2022) reported a 2.7-fold lower risk in suffering a HSI in the intervention group compared with the control. Although this reduced risk was not significant ($p = 0.12$). It should be noted here that when adaptations in eccentric knee flexor strength were adjusted to account for baseline differences between the low and high compliance groups, the magnitude of effect was reduced (unadjusted mean difference 26.5%; 95% CI = 7.1% – 49.9%; $g = 1.11$; mean difference adjusted for baseline, 15.5%; 95% CI, 1.2% – 29.8%), but still significantly higher in the high compliance group ($p \leq 0.01$; $g = 0.88$). The comparison of training compliance also supports the observations from Ripley et al. (2021), that practitioners may have some flexibility around athlete compliance and frequency of NHE, with compliance rates of >50.1% and training frequencies of <3 weeks/session having positive effects on HSI incidence, but that compliance above this threshold may yield a more positive adaptation in strength levels.

However, CHAPTERS 3-4 also indicated that practitioners do not focus on the NHE as the only method of development of hamstring strength. It seems evident that practitioners also perceive there to be benefits of the use exercises such as the RDL, which may be due to previous research (Hegyi et al., 2018) that has indicated that region-specific neuromuscular excitation of the BFLH is significantly higher in the distal region than the middle or proximal regions during the NHE ($p \leq 0.05$; $d = 0.38$-1.25) and Pincheira et al. (2022) reported significant and very large ($p < 0.001$; g 3.73) increases in distal region BFLH FL, but no significant (p 0.21; $g = 0.50$) changes in central region BFLH FL, indicating preferential adaptations in the distal region. Furthermore, a previous study by Lee et al. (2018) have demonstrated the potential for the generation of larger ($g = 6.72$) hip extensor (0.86 ± 0.07 Nm·kg·cm^{-1}) torques compared with knee flexor torques (0.28 ± 0.1 Nm·kg·cm^{-1}) during the RDL. Additionally, the RDL is also associated with significant-large ($p \leq 0.05$; $g = 1.88$) increases in peak normalised muscle forces in the gluteus maximus compared to in the NHE (Van Hooren et al., 2022) which may provide additional training benefits given the role of the gluteus maximus in generating forceful hip extension during tasks such as sprinting and jumping. However, it should be highlighted here that the same study did find that normalised hamstring muscle forces were larger during the NHE than in the RDL, ($p \leq 0.05$; $g = 1.98 – 2.03$) likely due to the differences in exercise intensity (1 RM RDL compared with supramaximal nature of the NHE).

Currently, only Marchiori et al. (2022) have directly compared adaptations in strength, muscle architecture or countermovement jump (CMJ) performance between NHE and RDL training interventions, indicating that while there was significant, yet trivial-moderate ($p \leq 0.05$; d 0.04 – 0.76) improvement within each intervention group, there were no significant ($p \geq 0.05$; $g = 0.36$ - 1.10) between group differences, indicating that there does not seem to be any superior benefit of the NHE over the RDL or visa-versa. It should be noted there that the magnitude of change (small-moderate), does indicate a meaningful effect even if it did not meet the threshold for statistical significance. This may be due to two participants withdrawing from the RDL group prior to post-test due to injury, resulting in a final $n = 11$, which likely under-powered the statistical analyses. On the other hand, the volume-loads in the study of Marchiori et al. (2022) could be questioned as the volumes (matched across groups) progressed from 2x8 repetitions twice per week (32 weekly repetitions) in week one to 4x12 repetitions twice per week (96 weekly repetitions) in week five. The high volume of NHEs raises questions around the intensity of the repetitions, particularly in the high-volume sessions and whether greater adaptation may have been achieved had the NHE load been progressed using the addition of external loads (Bourne, et al., 2017; Duhig, et al., 2019). The RDL loads were fixed at 75% 1RM (~ 10 RM) which would indicate that participants would have repetitions in reserve in the earlier weeks (due to only performing sets of eight repetitions) of the study, but then were likely underloaded by week five, as the programme detailed that participants were performing sets of twelve repetitions with their baseline 10 RM load, which indicates that their level of strength had increased as twelve repetitions at 10 RM should not be possible. However, Richens and Cleather (2014) have reported that participants are able to complete more repetitions than is indicated in traditional repetition maximum tables.

For instance, in the leg press exercises it was reported that endurance-athletes completed 39.9 (± 17.6) repetitions at 70% 1 RM in the leg press and weightlifters completed 17.9 (± 2.8) repetitions. However, it should be noted that the ability to perform more repetitions has been shown to be largely dependent on training status, and that untrained participants are unlikely to be able to complete more than the expected number of repetitions (Kraemer et al., 1999; Pick and Becque. 2000) Therefore, while the findings of Marchiori et al. (2022) provide an interesting comparison between the two exercises in volume-matched conditions, there remains questions around the ecological validity of the programmes. There also remains questions around what magnitude of adaptation may have occurred if the exercises were volume-load matched. However, to sufficiently load-match a comparison between a truly supramaximal eccentric NHE and an RDL would require the use of weight releasers to allow the eccentric phase of the RDL to be performed at a load > 1 RM.

Three author groups have investigated comparisons of sprint training versus NHE on either hamstring muscle architecture and running performance (Mendiguchia et al., 2020) knee flexor torque (Sancese et al., 2023) or a combination of hamstring strength and sprint performance (Freeman et al., 2019) with varying results. Freeman et al. (2019) found significant yet small (p = 0.01; d 0.26-0.39) improvement in eccentric knee flexor strength in both sprint and NHE groups, but no significant (p = 0.100-0.860; d = 0.00 – 0.86) changes in sprint performance. Sancese et al. (2023) reported significant ($p \leq 0.05$) yet small increases in eccentric knee flexor torque in both sprint (g = 0.41) and NHE (g = 0.31) groups at $60°\cdot^{-1}$ but significant and meaningful improvements in knee flexor torque at $180°\cdot^{-1}$ were only reported in the NHE group (g = 0.89). Additionally, Sancese et al. (2023) reported no changes in 30 m sprint performance ($p \geq 0.05$; g = -0.16 – 0.73). Mendiguchia et al. (2020) reported small decreases in sprint performance (g = 0.28 – 0.49) and BFLH FL (g = 0.69) in the NHE group and small-moderate increases in the sprint group (sprint performance, g = 0.64 BFLH FL, g = 1.05). Overall, it has been reported by Bautista et al. (2021) in a systematic review and meta-analysis (g = 0.61; SMD -0.04 s; 95% CI -0.09 - -0.01) that across the pooled investigated sprint distances, NHE training can lead to moderate beneficial adaptations.

Further to those authors that have investigated the effects of single intervention resistance training or isolated HSR training in HSI risk factors or markers of athletic performance, only Ripley et al. (2023) has investigated the effects of combined resistance and HSR training. Ripley et al. (2023) investigated the use of a more ecologically valid resistance training programme (including RDL, weightlifting derivatives and squat movements) which is likely more representative of strength training approaches in applied practice. However, Ripley et al. (2023) also supplemented resistance training with either NHE training or HSR. Ripley et al. (2023) reported that resistance training with the addition of either NHE or sprinting yielded significant, small-large improvements in hamstring muscle architecture, eccentric knee flexor strength, CMJ take-off velocity, (but only significant improvements in mean propulsive force in the NHE group only), IMTP peak absolute and relative net force and 20 m sprint time.

Previously, it has been suggested by the likes of Morin et al. (2011; 2012) and Rabita et al. (2015) that the primary mechanical determinant of effective forward acceleration and forward running velocity is the ability to apply more horizontally oriented the ground reaction force vector. For instance, Morin et al. (2011) investigated the ‘effectiveness’ of force application during maximal running by calculating the ratio of forces (horizontal force production divided by total force production) and the slope of this ratio at increasing running velocities and found significant correlations ($r \geq 0.731$; $p \leq 0.01$) between peak and mean 100 m velocities and four s distance, however no significant correlations were reported between 100 m sprint performance and total force production ($r = 0.390 – 0.520$; $p \geq 0.05$). The results of Morin et al. (2011) were also supported by Rabita et al. (2015) that reported similar correlations between sprint performance and horizontal application of the ground reaction force vector ($R^2 = 0.892 – 0.950$; $p \leq 0.05$) Morin et al. (2012) also investigated the correlations between force application characteristics and 100 m sprint performance in a cohort of elite national and international level sprinters. Their results supported their previous hypotheses given that the ability to horizontally orientate the ground reaction force vector during sprinting was significantly correlated ($R^2 \geq 0.683$; $p = 0.018$) to 100 m sprint performance, whereas the magnitude of the resultant was not significantly correlated ($R^2 \geq 0.408$; $p – 0.160$) to performance.

Nagano et al. (2014) investigated the kinetics of the hip muscles during sprint running (9.52 $m \cdot s^{-1}$) and reported that both the gluteus maximus and bicep femoris were the primary contributors to hip extension during the stance phase of the running cycle. It was reported that the mean muscle tendon unit forces of the bicep femoris and gluteus maximus during the stance phase of the running cycle were 3.64 $N \cdot kg^{-1}$ and 1.92 $N \cdot kg^{-1}$, respectively, although it was reported that the bicep femoris does experience a second peak of 10.5 $N \cdot kg^{-1}$ during the swing phase (80.3% of the total gait cycle). The results of Negano et al. (2014) therefore seem to support the importance of strength development in both the hamstrings and gluteal muscles given their role in generating hip extension during the stance phase of the running gait, which is key in the application of horizontal forces.

Similarly, Lees et al. (2004) investigated joint kinetic contributions during the CMJ and reported that as jump height increased, there was a significant-large ($p \leq 0.001$; $\omega^2 = 0.79$) increase in hip extensor positive work done, whereas there was a significant-moderate increase in positive work at the ankle ($p = 0.034$; $\omega^2 = 0.11$) with increasing jump height and no significant (small) changes in positive work done at the knee ($p = 0.234$; $\omega^2 = 0.05$). The findings of Lees et al. (2004) indicate that hip extension is a primary determinant of vertical jump performance, and alongside the aforementioned contributions of hip extension to running performance, indicate a need to develop hip extensor strength to aid the enhancement of athletic tasks just as maximal jumping and sprint running.

The existing literature indicates that isolated resistance training using the NHE, isolated HSR and the addition of either HSR or the NHE to a training programme can mitigate HSI risk and improve maximal sprint performance as well as other areas of athletic performance such as jumping and general lower body strength. However, a comparison of combined HSR with NHE training to combined HSR with a hip hinge focus to resistance training, given the potential for hip hinge focused resistance training to increase BFLH neuromuscular excitation is lacking. Additionally, the benefits of incorporating curvelinear (given earlier suggestions of Filter et al. (2020), that curvelinear running can increase BFLH excitation) running into the HSR training is also yet to be investigated.

8.3 Aims and Hypotheses.

The aim of the current study was to investigate and compare the effects of two ecologically valid resistance training programmes (one with a knee flexor bias and one with a hip hinge bias) combined with curvelinear high-speed running on hamstring strength, sprint performance, jump performance and lower body strength.

It was hypothesised that the NHE group would experience the greatest improvement in eccentric knee flexor strength due to the specificity of the NHE training to the assessment method as well as the supramaximal nature of the NHE for the duration of the training programme compared to submaximal RDL training.

It was hypothesised that the RDL group would experience the greatest increases in sprint, jump and lower body strength performance due to the concurrent hip extensor and knee flexor loads associated with the RDL.

Finally, it was hypothesised that both intervention groups would experience greater increases in all strength and performance measures over the control group due to the additional eccentric loading bias in both interventions.

8.4 Methods

8.4.1 Participants

An intervention design with pre and post measures was employed in the present study. A total of 37 participants (TABLE 8-1) volunteered to participate in the study. An *a-priori* sample size estimation was conducted (G*Power version 3.1, University of Dusseldorf, Germany) based on a minimum acceptable power of 0.80 with *alpha* set as 0.05 and a desired effect size of 1.20 which showed a sample of twelve participants required in each of the three groups. A desired effect size of 1.20 was selected based on the Cuthbert et al. (2019), as the studies that reported positive adaptations in knee flexor strength all exceeded the threshold for a ‘large’ magnitude of effect (i.e., $g \geq 1.20$). Therefore, it was decided that the use of a desired effects of 1.20 would allow the study to be sufficiently powered to detect such a magnitude of change in the primary variable relating to risk of HSI. All participants were recruited from a football academy competing in the Northwest Youth Alliance Premier Division in the United

Kingdom. Participants were randomly allocated (following pre-intervention testing) to one of three intervention groups using an online random group generator tool (https://www.randomlists.com/team-generator). All three groups participated in combined resistance and high-speed running training throughout the intervention period. While the high-speed running training was identical for all three groups, the resistance training sessions differed with one group (RDL) included two weekly exposures to the RDL as a hip-hinge focus to the training programme, the NHE group included two weekly exposures to the NHE as a knee flexor dominant focus to the training programme and the control group included two weekly exposures to the reverse lunge as a non-hamstring dominant exercise (See FIGURE 8-1 for a visual representation of the study design). Details of the training programmes are presented in TABLES 8-2; 8-4. All participants were in overall good health, which was ascertained through the completion of a Health Screening Questionnaire (APPENDIX 3.0). All participants reported having a history of resistance training and high-speed running training of between one to two years based on their involvement in the football academy.

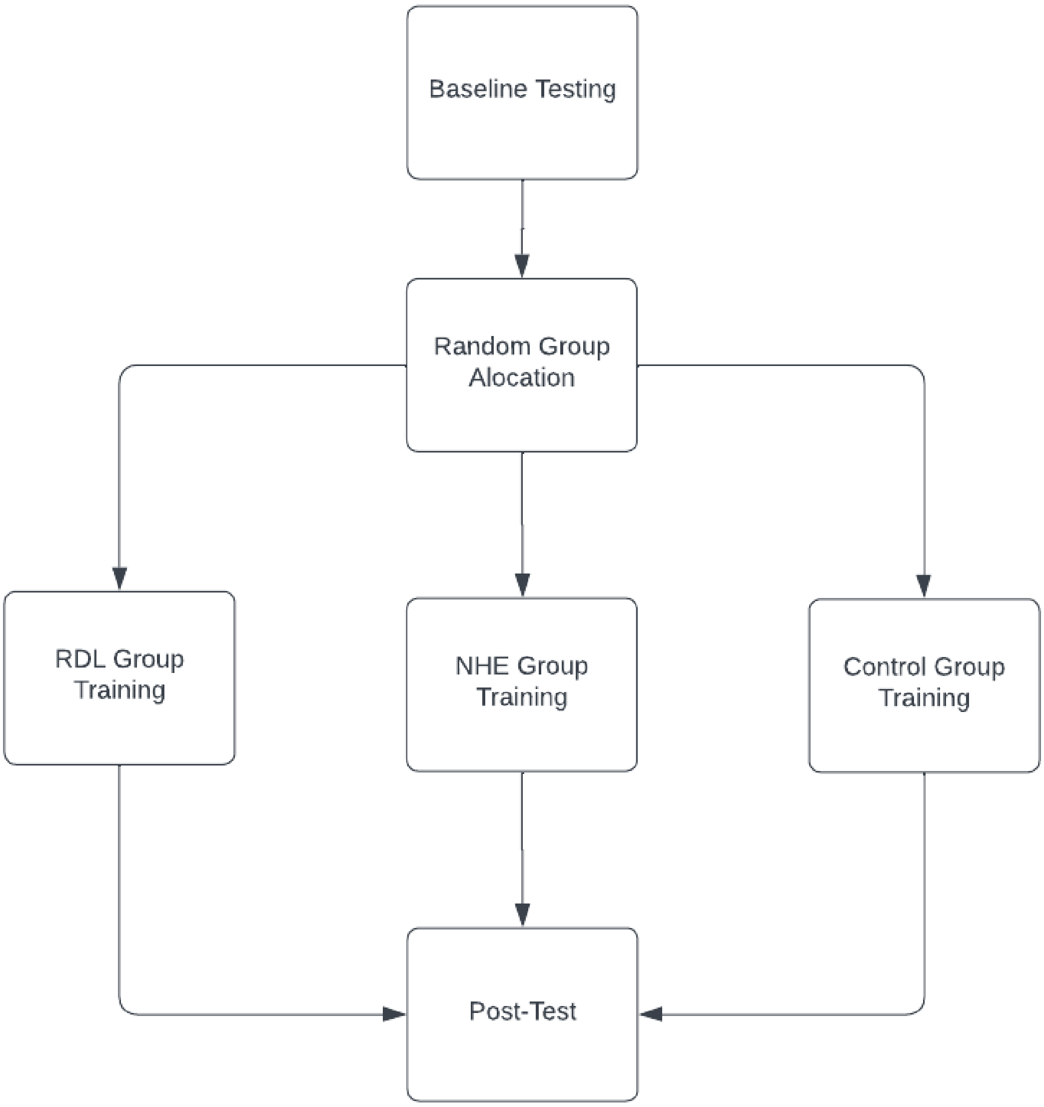


Figure 8-1 A flow diagram of the study design.

The study achieved institutional ethical approval (Application ID: 6651). Prior to agreeing to take part in the study, all participants received a written participant information pack accompanied by an in-person presentation by the lead researcher to illustrate the purpose of the research, during which participants were offered the opportunity to ask questions. The parent / legal guardian of any potential participant that was under the age of 18 years also received an information pack and was provided with the opportunity to contact the lead researcher or supervisory team with any questions. All potential participants and legal guardians were allowed at least 24 hours to consider the information provided before completing written informed consent to participate. The study also conformed to the principles of the Declaration of Helsinki (2013). All participant characteristics are presented in TABLE 8-1. A series of one-way ANOVAs revealed that there were no significant differences between the three groups for height (p = 0.229) or body mass (p = 0.912) at baseline.

Table 8-1 Descriptive participant characteristics for each of the three groups.

	RDL Group (n = 13)	NHE Group (n = 11)	Control Group (n = 13)
Age (years)	16.9 ± 0.9	17.2 ± 0.8	17.1 ± 0.6
Height (cm)	179.0 ± 8.5	175.5 ± 5.1	180.4 ± 6.5
Mass (kg)	70.6 ± 6.9	71.3 ± 5.9	69.9 ± 9.8

8.4.2 Data Collection

Prior to any data collection, all participants participated in a standardized warm-up which consisted of reverse lunges, bodyweight squats and submaximal CMJs. Following the warm-up, participants completed three repetitions of the CMJ, countermovement rebound jump (CMJ-R), isometric mid-thigh pull, and 20 m maximal sprint. Participants also completed four repetitions of the NHE with the first repetition excluded from analysis to improve reliability as suggested by Ross et al. (2020; CHAPTER 7) Participants completed each of the five tests in a randomised order. Participants received an explanation and video demonstration of each of the tests during the presentation that was provided during participant recruitment. Additionally, participants all received a physical demonstration and explanation of each test on the day of baseline testing. None of the participants identified that they had any previous experience in completing any of the tests.

CMJs, CMJ-Rs and IMTP were all conducted using Hawkins-Dynamics portable force plate system (3rd Generation, Westbrook, Maine, USA) consisting of two portable adjacent force plates. Participants performed the tests with one foot on each individual force plate. Force data was captured at 1000 Hz and pre filtered with a 50 Hz cut-off frequency. The Hawkin Dynamics portable force plate system has been previously validated against the 'gold standard' of in-ground force plates (Badby et al. 2023). Additionally, force-time metric analysis of the Hawkin Dynamics software have been validated against a standardised MATLAB script with ≤1% differences in all assessed metrics across the two software packages. Merrigan et al. (2022; 2024). During the CMJ and CMJ-R, the force plates were positioned within foam surrounds to ensure participant safety in case participants failed to land back on the force plates.

For the CMJ trials, participants stood upright (extended hips and knees) with their hands on their hips. Participants were instructed to stand completely still for at least one second at the start of data collection to allow for the calculation of system mass (equivalent to body weight) and to allow for identification of movement onset. Participants were provided with an audio-visual cue to jump in which ensured 1 second of quiet stance followed by an on-screen flash and audible beep from a tablet computer. Participants were cued to jump "as fast and high as possible". The verbal cue was used to promote the intent of the jump to achieve the maximal jump height achievable, while also minimising time to take off, without favouring either a fast or high strategy independently (Jidovtseff et al., 2014).

For the CMJ-R, participants were instructed to complete a CMJ as described above, however participants were cued to immediately jump as high as fast as possible upon landing from the initial CMJ, while minimising ground contact time. To the author's knowledge, there is only one previously published study that has investigated the CMJ-R (Xu et al. 2023). Xu et al. (2023) established good-excellent reliability (ICC 0.79-0.98) and acceptable coefficients of variation (%CV ≤ 9.83) for CMJ-R variables including jump height, ground contact time and reactive strength index of the second jump.

For the IMTP, participants were instructed to adopt a posture which replicates the start of the second pull phase of the clean. As participants were not familiar with traditional weightlifting positions, the assessor selected a bar height that allowed the participant to adopt a posture where the bar was positioned around the height of the start of the second pull phase, with the knees flexed and in front of the bar, the ankles in full dorsiflexion and the shoulders over or slightly in front of the bar in the sagittal plane. A cold rolled steel bar was secured in an IMTP rig (Absolute Performance, Cardiff, UK) with the hands fixed to the bar using lifting straps. Comfort et al. (2019) Participants stood with one foot on each of the force plates and completed two warm-up trials at 50% and 75% of perceived maximal effort with each trial separated by a one-minute rest period. Participants were instructed not to lean on the bar to avoid underestimation of system mass. Participants were also instructed not to pull on the bar prior to the trial, however, were given leeway of ≤50 N of pretension. (Dos'Santos et al., 2017) Participants were provided with an audio-visual cue to initiate the pull in which ensured one second of quiet stance followed by an on-screen flash and audible beep from a tablet computer. Participants were cued to pull up on the bar while pushing the feet into the force plates as hard and fast as possible. Comfort et al. (2019) Participants completed three maximal effort trials with strong verbal encouragement. Each trial lasted approximately five seconds.

Eccentric knee flexor strength was assessed via the NHE performed on the NordBord (Vald Performance, Newstead, Australia), with a sample frequency of 50 Hz. The NHE was performed with the participant starting in a kneeling position with the knees on the padded surface of the NordBord. The ankles were secured in position by individual braces, attached to uniaxial load cells. The ankle braces were positioned perpendicular to the shank for testing to ensure that all force generated by the knee flexors was applied and recorded purely along the long axis of the load cell once the ankles were positioned appropriately. Once in position, participants were instructed to place their hands out in front of their torso, with the shoulders in a neutral position, elbows flexed to approximately 90˚ to allow the use of the hands to cushion their descent at the end of the movement. To complete the NHE participants were instructed to learn forward as slowly as possible while maintaining a neutral (0° extension) hip position and an upright trunk, while maximally resisting this movement using the knee flexors of both limbs, until unable to continue to resist knee extension, or until the movement was completed by reaching approximately 0˚ knee extension.

All 20 m sprint trials were conducted on an outdoor 3G football pitch, which was also the same pitch on which participants conducted their regular football training sessions and home fixtures. Sprint trials were recorded using a Brower single-photocell electronic timing gate system (Draper, Utah, USA), which has been previously validated (Waldron et al., 2011) against GPS. Timing gates were positioned at 0 m, 5 m, 10 m and 20 m. Emitters and reflectors were positioned approximately 2 m apart and approximately at hip height. Participants completed two warm-up trials at 50% and 75% of perceived maximal intensity. Following the warm-up trials, participants completed three maximal effort trials with a three-minute rest period between trials. Participants were cued to start trials in a two-point stance with the front foot positioned on a marker 0.3 m from the first (0 m) gate (Waldron et al., 2011). Any trials that were initiated by a countermovement (i.e., backward step) were excluded and repeated and all participants received strong verbal encouragement for the duration of each trial.

8.4.3 Data Analysis

All measures of CMJ, CMJ-R and IMTP performance were calculated through Hawkins-Dynamics software but for clarity, the methods for determining each measure are outlined below. To calculate take-off velocity, first body weight is subtracted from the vertical force. The remaining force is then divided by body mass and integrated using the trapezoid rule. For the calculation of mean propulsive force and mean braking forces, individual subphases of the CMJ are established within the Hawkins Dynamics software. Firstly, the weighing phase is established by using the one s period with the lowest standard deviation in the vertical ground reaction force, which then redefines the start and end of the weighing phase. The unweighting phase is identified between the onset of movement, defined as the instant at which the vertical ground reaction force (vGRF) exceeds five SDs of bodyweight (McMahon et al., 2018) and the peak negative centre of mass velocity and a return of the vGRF to bodyweight (McMahon et al., 2018). The unweighting phase is followed by the braking phase, which is identified between the peak negative centre of mass velocity and zero centre of mass velocity. Therefore, the average force during this period was used to establish mean braking force. The propulsive phase is considered between the end of the braking phase and take-off, which is defined as the point at which the vGRF reaches 25 N which is followed by the participant leaving the force plate with the intention of achieving maximum positive centre of mass displacement. McMahon et al. (2018)

Therefore, mean propulsive force was calculated as the average force during this period. Modified reactive strength index (RSImod) from the CMJ was calculated by dividing jump height by time to take off (between start of unweighting phase to end of the propulsive phase). For the CMJ-R, a 25 N threshold was used to define touchdown after the first jump and then take-off for the second jump RSI was calculated for the rebound portion of the movement, jump height of the second jump was divided by the time between landing from the initial jump and end of the propulsive phase of the second jump.

Raw force-time curves from the NHE trials were processed in Microsoft Excel, the mean force plus five times the standard deviation (±) was calculated from the initial second of data which corresponded to when participants were knelt upright (i.e., knees, hips, and upper body in vertical alignment) before they commenced the NHE. This calculation created a ‘force threshold’, with the onset of movement defined as the instant at which force exceeded this value. The PF was defined as the highest force after the onset of movement. The PF was used as a reference point for the end of the NHE trial because this instant was assumed to be immediately proceeded by falling to the ground (i.e., when participants were no longer able to resist knee extension). Processed forces from the NHE trials were subsequently divided by each participant’s body mass to obtain relative eccentric knee flexor force (N·kg). For the IMTP, the peak forces achieved across the entire force-time curve were used to establish peak net force. Peak net force was divided by body mass to establish peak relative net force.

For the IMTP, the onset of the movement was identified as the moment at which the vGRF exceeded 3 SDs of bodyweight (obtained during the one s quiet stance period). The maximum force generated during the 5 second maximum effort was used to define absolute peak force, which was then normalised to body mass. Body mass was defined as the bodyweight obtained during the one s quite stance period, divided by acceleration due to gravity (9.81 m·s^2). Following each IMTP trial, the force-time curve was visually inspected to ensure that there was no countermovement proceeding the pull and that the peak force did not occur at the end of the pull, as recommended by Comfort et al. (2019).

8.4.4 Training Programme

Throughout the intervention period all three groups took part in a combined resistance training and high-speed running programme. All sessions took place on a Monday and a Friday afternoon and were led by the candidate. While all participants reported that they were familiar with both resistance and high-speed running training through their involvement with the football academy, the club did not have any set programme in place, therefore it was not clear to what extent each individual was accustomed to progressive loading. As a result, the intervention programme was developed to progressively increase load in the resistance elements, while maintaining a consistent volume. Each resistance training session was made up of three separate exercises. The first two exercises on each day (jump shrug and hamstring catch on day one and front squat and knee slides on day two) were identical for all three groups with the third exercise distinguishing between each group; the RDL and NHE for the RDL and NHE group and the reverse lunge for the control group.

The programme was designed to elicit adaptations in peak force generating capacity of the lower body. On a Monday, each group completed jump shrugs and the hamstring catch in addition to their group-determined additional exercise (RDL, NHE or reverse lunge). The jump shrug was selected as an alternative and arguably less technically challenging alternative to the power clean given the participants' lack of experience with more traditional weightlifting movement patterns and would therefore allow a similar movement including concurrent forceful extension of the ankle, knee and hip from a mid-thigh position, without the need to catch the barbell in a front rack position. Although the jump shrug has been recommended as a lift best suited for training for adaptations in speed-strength (Suchomel et al., 2015; Suchomel et al., 2017), jump shrug loads of between 65-80% of hang clean loads have been recommended as suitable for adaptations in peak force (Suchomel et al., 2013; Comfort et al., 2023), therefore jump shrug loads progressing from 70-80% were programmed to allow for developments in peak force, given that the participants' speed training was completed in the HSR sessions. The hamstring catch was programmed on the Monday session to provide a strength-focused stimulus to the hamstring and gluteal muscles, while minimising eccentric lengthening of the muscles to reduce the risk of muscle soreness given that competitive fixtures were usually played on a Sunday.

On training day two, the front squat was programmed, given the role of the knee extensors in running and vertical jumping (Lees et al., 2004; Nagano et al., 2014). Again, due to the participants' lack of experience in loaded squatting movements, it was decided that the volume would remain relatively low throughout the programme (three sets of five repetitions), and the load would gradually increase from 70 - 80% of 1 RM. The use of lower loads in weeks one – three allowed for focus on movement proficiency before progressing to 80% 1 RM in week four, allowing for more of a strength focus, while still allowing one repetition in reserve, given that 85% of 1 RM is approximately equivalent to 6 RM. (Haff and Triplett, 2016) Knee slides were also programmed on training day two to provide an eccentrically bias resistance training stimulus to the hamstring muscles, without preferentially exciting the medial hamstrings over the lateral hamstrings or visa versa. (Zebis et al., 2013)

Prior to the first training session, participants completed incremental warm-up sets for all externally loaded exercises, starting with an unloaded barbell (e.g., back squat, jump shrug, RDL) or body weight only (e.g., reverse lunge). Load was then incrementally increased by ~5 – 10 kg until a load was established at which participants could complete a set of five repetitions (i.e., ~87.5% of 1 RM). These values were then used to estimate 1 RM and prescribe external loads to be used for the remainder of the programme. While 1 RM testing has been reported to be safe and appropriate for healthy adolescents (Faigenbaum et al., 2012), the use of submaximal efforts to estimate 1 RM was deemed appropriate here as to minimize acute spikes in maximal loads given the uncertainties around the maximal effort resistance training status of the participants.

Table 8-2 The weekly resistance training programme followed by the RDL group. Session volume-loads are expressed as sets x reps and estimated one repetition maximum percentages.

RDL Group						
Day 1						
Week	1	2	3	4	5	6
Jump Shrug	3x3 70%	3x3 70%	3x3 75%	3x3 80%	3x3 80%	3x3 80%
Hamstring Catch	3x5	3x5	3x5	3x5	3x5	3x5
RDL	3x5 75%	3x5 80%	3x5 85%	3x5 87%	3x5 87%	3x5 87%
Day 2						
Week	1	2	3	4	5	6
Front Squat	3x5 70%	3x5 70%	3x5 75%	3x5 80%	3x5 85%	3x5 85%
Knee Slides	3x5	3x5	3x5	3x5	3x5	3x5
RDL	3x5 75%	3x5 80%	3x5 85%	3x5 87%	3x5 87%	3x5 87%
Weekly Volume	78	78	78	78	78	78

Table 8-3 The weekly resistance training programme followed by the HHE group. Session volume-loads are expressed as sets x reps and estimated one repetition maximum percentages.

NHE Group						
Day 1						
Week	1	2	3	4	5	6
Jump shrug	3x3 70%	3x3 70%	3x3 75%	3x3 80%	3x3 80%	3x3 80%
Hamstring Catch	3x5	3x5	3x5	3x5	3x5	3x5
NHE	1x4	1x4	1x4	1x4	1x4	1x4
Day 2						
Week	1	2	3	4	5	6
Front Squat	3x5 70%	3x5 70%	3x5 75%	3x5 80%	3x5 85%	3x5 85%
Knee Slides	3x5	3x5	3x5	3x5	3x5	3x5
NHE	1x4	1x4	1x4	1x4	1x4	1x4
Weekly Volume	62	62	62	62	62	62

Table 8-4 The weekly resistance training programme followed by the Control group. Session volume-loads are expressed as sets x reps and estimated one repetition maximum percentages.

Control Group						
Day 1						
Week	1	2	3	4	5	6
Jump Shrug	3x3 70%	3x3 70%	3x3 75%	3x3 80%	3x3 80%	3x3 80%
Hamstring Catch	3x5	3x5	3x5	3x5	3x5	3x5
Reverse Lunge	3x5 75%	3x5 80%	3x5 85%	3x5 87%	3x5 87%	3x5 87%
Day 2						
Week	1	2	3	4	5	6
Front Squat	3x5 70%	3x5 70%	3x5 75%	3x5 80%	3x5 85%	3x5 85%
Knee Slides	3x5	3x5	3x5	3x5	3x5	3x5
Reverse Lunge	3x5 75%	3x5 80%	3x5 85%	3x5 87%	3x5 87%	3x5 87%
Weekly Volume	78	78	78	78	78	78

The HSR sessions were designed to be progressive over the training intervention. The sessions were progressed based on ‘levels’. Level one started with 10 m zones marked out for linear acceleration and decelerations with a 25 m zone marked to maintain perceived maximal velocity running around a 20° curve. Each session consisted of four total HSR repetitions, two of which were left-hand curves and two were right-hand curves. For level three, the acceleration zone was removed to cue the participants to sprint with maximal intensity from the start of the repetition and the deceleration zone was shortened to 2 m to cue participants to brake with maximal intent and stop in a forward lunge stance as soon as possible. Level one was used consistently across all Monday sessions as participants played competitive football fixtures on Sundays. Therefore level 1 was used to ensure participants still received a HSR stimulus but propulsive and braking impulses during the acceleration and deceleration periods were lower than levels two and three to reduce the risk of muscle soreness. Additionally, acute spikes in HSR and sprinting volumes have been observed to be associated with increased risk of injury (Malone et al. 2018).

Curvelinear sprinting was selected for a number of reasons (i) curvelinear running has been shown (Filter et al. 2020) that curvelinear sprinting has been shown to increase neuromuscular excitation in the BFLH and ST, with the outside leg eliciting significant-small ($p \leq 0.05$; d – 0.43) increases in BFLH excitation and significant, but trivial ($p \leq 0.05$; $d = 0.14$) increases in ST excitation. (ii) It has been observed (Caldbeck, 2020) that approximately 85% of maximal velocity running efforts in elite level soccer are curvelinear in nature. Therefore, it was hypothesized that curvelinear HSR could potentially further increase neuromuscular adaptations to the training stimulus as well as provide a more contextual training environment.

Table 8-5 The weekly high-speed running programme followed by all participants. Volumes are expressed as sets x reps with loads expressed in levels 1-3. Each set consisted of two repetitions with a left-hand curve through the maintain zone and two repetitions with a right-hand curve through the maintain zone.

Week	1	2	3	4	5	6
Day 1	L1	L1	L1	L1	L1	L1
	1x4	1x4	1x4	1x4	1x4	1x4
Day 2	L1	L1	L2	L2	L3	L3
	1x4	1x4	1x4	1x4	1x4	1x4
Weekly Distance (m)	360	360	320	320	288	288

Sprint Levels	Acceleration zone (m)	Curvelinear Maintain (m)	Deceleration zone (m)
L1	10	25	10
L2	5	25	5
L3	0	25	2

Unfortunately, trade union strikes affecting the British rail network were announced for the scheduled post-test day. Given that a large portion of the study participants relied on the rail network to commute to training, it was decided that the post-test day should be rescheduled to minimise participant drop-out. As a result of this participants did not complete the planned training session of ‘day two’ of week six. There was a knock-on consequence of rescheduling of the post-test as during the period in which the study was conducted the club were in the process of finalising decisions on which academy players would be offered professional playing contracts. As a result, some of the study participants were scheduled to take part in aspects of first-team training on the rescheduled post-testing day. As a result, some participants were not available to complete all post-tests. All participants that were present on the post-test day completed the sprint trials (as this was conducted on-pitch prior to training), but some participants did not complete all of the NHE, jump or IMTP trials.

For the purposes of clarity here, the number of participants included in the final analysis for each metric across all athlete tests is included in TABLE 8-6. The reasons for final numbers are detailed to allow the reader to understand the extent to which the adverse effects of the planned post-testing schedule had on the final analyses.

Table 8-6 The final number of participants (n) included in the statistical analysis for each test and each metric across each of the three groups and the associated reasons for inconsistent participant numbers across tests. 'lost to post-test' refers to the number of participants that did not complete a given test due to being required in the first-team training session.

		RDL		NHE		Control	
	Metric	Final *n*	Reason(s)	Final *n*	Reason(s)	Final *n*	Reason(s)
Countermovement Jump	Relative Mean Propulsive Force	6	2 statistical outliers removed 5 lost to post-test				1 statistical outlier removed
	Relative Mean Braking Force			8	3 lost to post-test	8	
	Take-Off Velocity	8	5 lost to post-test				
	RSImod						4 lost to post-test
Countermovement Rebound Jump	Rebound Jump Height Rebound Ground Contact Time	7	1 statistical outlier removed 5 lost to post-test	8	3 lost to post-test	9	4 lost to post-test
Eccentric Knee Flexor Force	Relative Eccentric Knee Flexor Force	9	4 lost to post-test	8	3 lost to post-test	7	6 lost to post-test
Sprint Performance	20 m Sprint Time	13	N/A	10	1 statistical outlier removed	12	1 lost to post-test
	0 – 5 m Sprint Time			11	N/A		
Isometric Mid-Thigh Pull	Peak Net Relative Force	6	1 statistical outlier removed 6 lost to post-test	8	2 statistical outliers removed 1 lost to post-test	8	1 statistical outlier removed 4 lost to post-test

8.4.5 Statistical Analyses

Reliability and absolute variability were assessed using the intra-class correlation coefficient ([ICC] two-way mixed effects model with absolute agreement), and percentage coefficient of variation (%CV). ICCs were interpreted based on the lower bound of the 95% CI as per Koo and Li (2016) on the following scale: <0.50, poor; 0.50-0.75, moderate; 0.75-0.90, good; >0.90 excellent. %CV of ≤10% were considered to be acceptable. Standard error of measurement was calculated using the following equation (Thomas, Nelson and Silverman, 2011).

$$SEM = SDpooled * \left(\sqrt{1 - ICC}\right)$$

Minimum detectable difference was calculated using the following equation as per Wier (2005)

$$MDD = SEM * 1.96 * \left(\sqrt{2}\right)$$

Given the potential for between-group variances in baseline performance, it was identified that these variances should be considered as a confounding variable. Therefore, the data was analysed using a linear mixed model (LMM), using the pre-post differences (i.e., change in scores from baseline to the post intervention measurement point) as the dependent variable, with group as the independent variable and baseline scores used as a covariate. (Vickers and Altman, 2001). LMM was selected as an appropriate statistical technique as it allows for the simultaneous modelling of fixed effects (group) and potential random effects (individual participant variance) and their interactions. LMM accounts for inherent dependency and correlation within the dataset (e.g., repeated measures) and clustering (group) of participants, whereas alternative methods such as the analysis of covariance (ANCOVA) assumes independence of measures which was not the case here. Additionally, the ANCOVA would assume a linear relationship between the covariate (baseline measure) and change score. Given the highly variable nature of athletic performance, the LMM was identified as a more appropriate means of analysis to allow for estimation of participant-specific slopes and interactions. For each individual independent variable, the Wald Z score was used to assess whether individual participants contributed to the model as a random factor. If the Wald Z score was significant (alpha ≤ 0.05), then participant was included in the model as a random effect, with group as a fixed effect. Based on the Wald Z scores, participant was included as a random factor in the model for analysis of 20 m sprint performance. Participant was not included as a random factor for any other measure as the Wald Z score exceeded 0.05.

Assumptions of the LMM were checked, firstly using the Shapiro-Wilk test to assess normal distribution of the change scores (*alpha* ≥ 0.05). To assess the homoscedasticity of the data, the residuals from the LMM were plotted against the predicted values of the model to visually assess normality of the residuals. If any assumptions of normality were not met, outliers were removed and the LMM was conducted.

For RSImod during the CMJ, it was found that there was no main effect for group, however the descriptive statistics indicated potential within-group differences between baseline and post-test. In this scenario, within group differences were analysed using paired-samples t-tests. Similarly, within group differences in 20 m sprint performance were analysed, however due to violating the assumptions of normal distribution, these differences were analysed using with Wilcoxon signed ranked test.

All group comparisons are presented as means and standard error, with uncertainty of estimates expressed as 95% confidence intervals. Magnitudes of effect were calculated using Hedges g. Effect sizes and associated 95% confidence intervals of the effect for group comparisons were conducted using https://www.estimationstats.com (Ho et al., 2019) The calculation of Hedges g was made using the following formula. Magnitude of effect was interpreted on the following scale: *trivial* ≤0.19; *small* 0.20 – 0.59; *moderate* 0.60 – 1.19; *large* 1.20 – 1.99; *very large* ≥2.00

$$g = \frac{(MeanPost - MeanPre)}{SDpooled}$$

8.5 Results

Table 8-7 Reliability of all measures at pre and post-test.

		Pre				Post			
		ICC (95% CI)	%CV (95% CI)	SEM (%)	MDD	ICC 95% CI	%CV	SEM (%)	MDD
Countermovement Jump	Relative Mean Propulsive Force	0.941 (0.892 – 0.970)	3.0 (2.6 – 3.3)	0.50 (2.16)	1.37	0.918 (0.837 – 0.962)	3.7 (3.3 – 4.0)	0.55 (2.39)	1.51
	Relative Mean Braking Force	0.879 (0.777 – 0.939)	6.3 (6.0 – 6.6)	0.96 (4.79)	2.65	0.938 (0.877 – 0.972)	5.7 (5.4 – 6.0)	0.69 (3.49)	1.90
	Take-Off Velocity	0.959 (0.918 - 0.981)	1.8 (1.4 – 2.0)	0.03 (1.39)	0.10	0.909 (0.819 - 0.958)	2.4 (2.1 – 2.7)	0.04 (1.73)	0.12
	RSImod	0.925 (0.857 - 0.964)	8.2 (7.9 – 8.5)	0.03 (5.49)	0.08	0.806 (0.614 - 0.911)	8.8 (8.5 – 9.2)	0.04 (7.66)	0.11
Countermovement Rebound Jump	Rebound RSI	0.893 (0.799 - 0.945)	10.7 (10.4 – 11.1)	0.11 (7.33)	0.31	0.801 (0.614 - 0.906)	13.5 (13.2 – 13.9)	0.13 (9.77)	0.37
	Rebound Jump Height	0.923 (0.826 – 0.967)	7.6 (7.2 – 7.9)	0.01 (4.68)	0.04	0.764 (0.542 – 0.888)	9.5 (9.1 – 9.8)	0.02 (7.13)	0.06
	Rebound Ground Contact Time	0.894 (0.810 - 0.944)	7.3 (7.0 – 7.7)	11.56 (5.39)	32.05	0.900 (0.806 – 0.953)	8.8 (8.5 – 9.2)	13.18 (6.03)	36.53
Eccentric Knee Flexor Force	Relative Eccentric Knee Flexor Force	0.945 (0.885 - 0.976)	5.7 (5.3 – 6.0)	0.19 (4.31)	0.53	0.953 (0.912 - 0.976)	7.1 (6.8 – 7.4)	0.21 (4.53)	0.58
Sprint Performance	20 m Sprint Time	0.496 (0.102 - 0.741)	3.0 (2.7 – 3.4)	0.09 (2.69)	0.25	0.869 (0.730 - 0.947)	2.5 (2.1 – 2.9)	0.05 (1.61)	0.14
	0 – 5 m Sprint Time	0.571 ((0.202 – 0.790)	6.9 (6.6 – 7.3)	0.05 (4.22)	0.14	0.881 (0.737 – 0.952)	5.1 (4.7 – 5.5)	0.03 (3.06)	0.09
Isometric Mid-Thigh Pull	Peak Net Relative Force	0.669 (0.295 – 0.843)	9.1 (8.7 – 9.4)	3.42 (13.32)	9.50	0.950 (0.881 – 0.979)	5.3 (5.0 – 5.6)	0.80 (3.10)	2.20

All measures of reliability can be found in TABLE 8-7. At baseline and post-test all CMJ measures were found to have acceptable-good reliability (based on the lower bound of the ICC 95% CI) and acceptable %CV. However, the %CV of RSI during the CMJ-R at baseline and post-test exceeded the threshold for acceptability, therefore RSI derived from the CMJ-R was excluded from further analyses and only the ground contact time and jump height of the second jump during the CMJ-R were analysed as they both has acceptable-good levels of reliability and acceptable %CV. Measures of relative peak knee flexor force had good-excellent reliability and acceptable %CV at baseline and post-test. 20 m and 5 m sprint times were associated with poor levels of reliability at baseline but improved to acceptable at post-test. The %CV for 20 m and 5 m sprint times were acceptable at baseline and post-test. Reliability of the IMTP was poor at baseline, but improved to acceptable at post-test, but %CV was acceptable at both time-points.

8.5.1 Body Mass

There was no significant change in body mass in any of the groups from baseline to post-test (TABLE 8-8).

Table 8-8 Descriptive statistics and statistical inferences of baseline and post-test body mass characteristics.

Group	Baseline Body Mass (kg)	Post-Test Body Mass (kg)	Mean Difference kg (95% CI)	*p value*	Hedges *g*
RDL	70.5 ± 6.9	70.8 ± 6.6	0.21 (-0.20 – 0.62)	0.282	0.04
NHE	71.3 ± 5.9	71.3 ± 5.5	0.00 (-0.82 – 0.82)	1.00	0.00
Control	69.9 ± 9.8	69.1 ± 10.1	-0.83 (-2.73 – 1.10)	0.360	0.08

8.5.2 Countermovement Jump

For relative mean propulsive force from the CMJ it was identified that two participants from the RDL group violated the assumptions of normality for the linear mixed model as the residuals were identified as significant outliers and were therefore removed from the analysis. Following removal of significant outliers, it was observed that there was a significant main effect for group (p = 0.032). Individual between-group (FIGURE 8-2) comparisons showed that the NHE group experienced significantly higher changes in relative mean propulsive force than the RDL group (p = 0.035; mean difference, 1.38 N.kg SE 0.50; 95% CI, 0.08 – 2.68 N.kg), which was observed as a large effect size (g = 1.37, 95%CI 0.21 – 2.43). There was no significant difference between the RDL and control groups (mean difference, -0.51 N.kg, SE 0.495; 95% CI, -1.81 – 0.79

N.kg; *p* = 0.958; *g* = 0.62, 95% CI -0.60 – 1.68), or between the NHE and control groups (mean difference, 0.88 N.kg, SE 0.459; 95% CI, -0.33 – 2.08 N.kg, *p* = 0.214; *g* = 0.82; 95% CI 0.24 – 1.80).

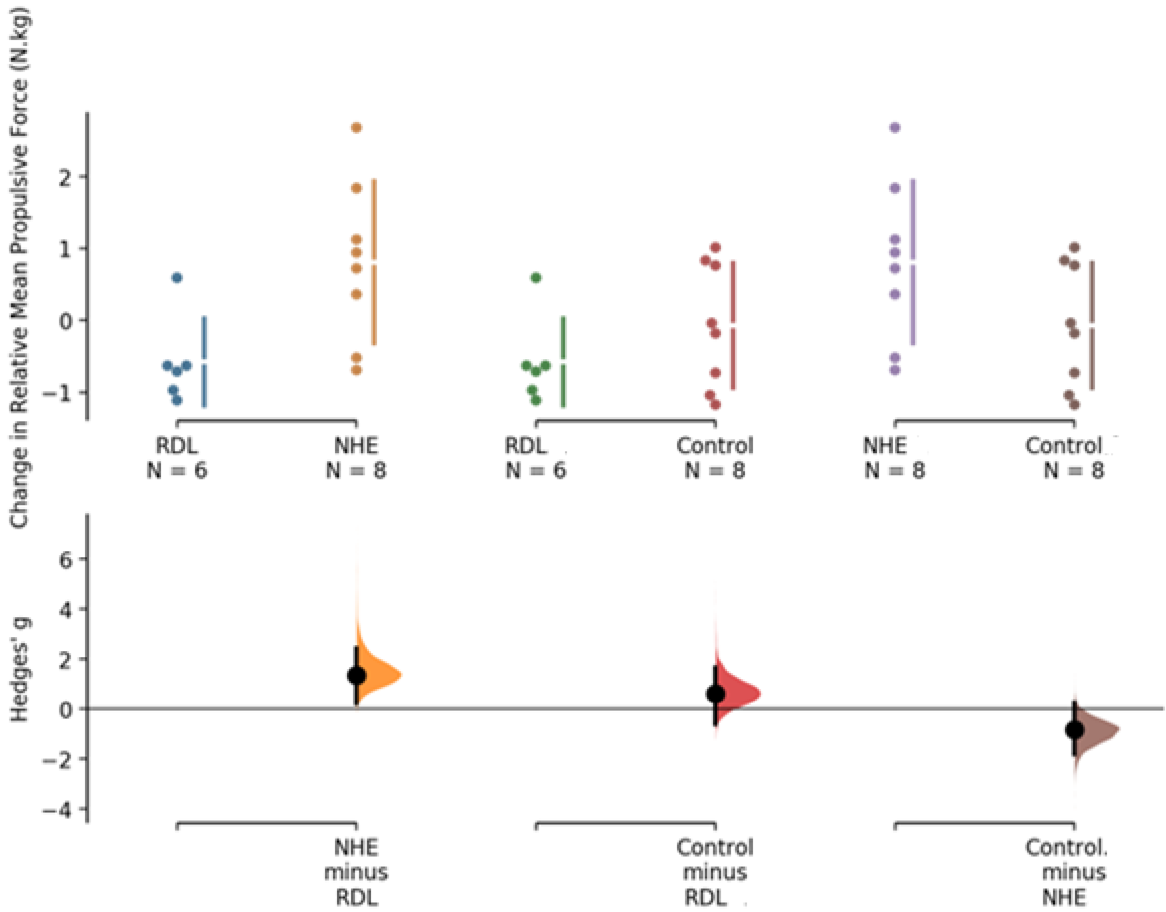


Figure 8-2 The between group pairwise comparisons for relative mean propulsive force during the CMJ. Individual participant scores are plotted on the upper axes. The lower axes show the Hedges g effect size which is depicted as a black dot; 95% Cis of the effect size are indicated by the vertical error bars.

There was no significant main effect for group for relative mean braking force in the CMJ (*p* = 0.617) Individual within group comparisons showed that there were no significant differences between baseline and post-test in any of the groups (TABLE 8-9).

Table 8-9 within group differences between baseline and post-test scores for relative mean peak braking force during the CMJ. Baseline and post-test scores are presented as means (±) with uncertainty of estimates expressed as 95% confidence intervals of the mean difference, magnitude of effect is expressed as Hedges g with associated 95% confidence intervals.

Group	Baseline (N.kg)	Post-Test (N.kg)	95% CI (N.kg)	*p*	*g* (95% CI)
RDL	19.96 (± 0.78)	19.69 (± 0.98)	-2.95 - 2.41	0.820	-0.10 (-1.07 - 0.61)
NHE	18.56 (± 1.41)	18.50 (± 2.25)	-1.61 - 1.47	0.914	-0.03 (-0.82 - 0.61)
Control	20.78 (± 3.78)	19.51 (± 2.66)	-4.01 - 1.30	0.272	-0.40 (-1.02 - 0.36)

There was no significant main effect for group for take-off velocity (p = 0.923) during the CMJ. Individual within group comparisons showed that there were no significant differences between baseline and post-test in any of the groups (TABLE 8-10).

Table 8-10 Within group differences between baseline and post-test scores for take-off velocity during the CMJ. Baseline and post-test scores are presented as means (±) with uncertainty of estimates expressed as 95% confidence intervals of the mean difference, magnitude of effect is expressed as Hedges g with associated 95% confidence intervals.

Group	Baseline (m·s)	Post-Test (m·s)	95% CI (m·s)	*p*	*g* (95% CI)
RDL	2.53 (± 0.24)	2.59 (± 0.14)	-0.24	0.322	0.27 (-0.13 - 0.89)
NHE	2.47 (±0.13)	2.52 (± 0.09)	-0.21	0.31	0.41 (-0.38 - 1.25)
Control	2.47 (± 0.15)	2.47 (± 0.18)	-0.19	0.915	-0.02 (-0.73 - 0.34)

For RSImod there was no significant main effect for group (p = 0.276). However, the descriptive statistics indicated potential within groups changes from baseline, therefore within group differences were further analysed. Individual paired samples t-tests indicated that although there was a non-significant-moderate difference, from baseline to post-test in the RDL and control groups (p = 0.278; g = 0.68; 95% CI -0.71 – 1.71 and p = 0.550; g = -0.36; 95% CI-1.44 – 0.39), respectively), there was a significant-moderate increase in RSImod from baseline to post-test in the NHE group (mean difference, 0.05 ;$p \leq 0.001$; 95% CI 0.035-0.079 g = 1.08; 95% CI 0.86 – 1.30).

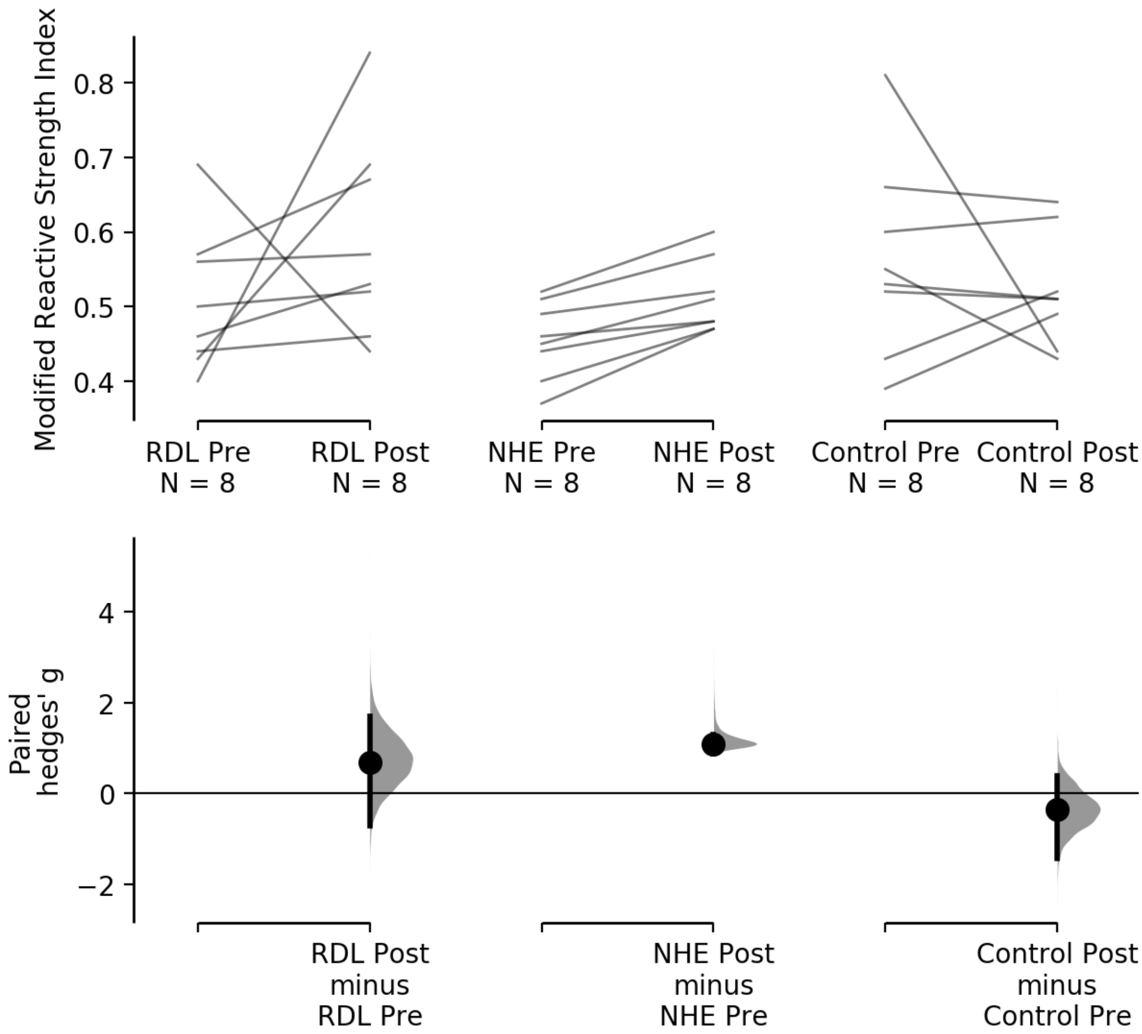


Figure 8-3 Within group pairwise comparisons for RSImod during the CMJ. Individual participant scores are plotted on the upper axes with each paired observation connected by a line. The lower axes show the Hedges g effect size which is depicted as a black dot; 95% Cis of the effect size are indicated by the vertical error bars.

8.5.3 Countermovement Rebound Jump

For the CMJ-R, there was no significant main effect for group for either jump height (*p* = 0.400). Within group comparisons revealed that there was no significant difference in the RDL group (*p* = 0.308, mean difference -0.02 ± 0.06 m; 95% CI -0.08 – 0.03 m) with the magnitude of effect observed to be small (*g* = 0.40, 95% CI -1.71 – 0.22). Similarly, no significant differences were observed in the NHE group (*p* = 0.710; mean difference, 0.01 ± 0.04 m; 95% CI -0.04 – 0.03 m), with the magnitude of effect observed to be trivial (*g* = 0.17; 95% CI -1.40 – 0.65). However, a significant-moderate reduction in jump height was observed in the control group (p = 0.024; mean difference, -0.38 ± 0.04 m; 95% CI -0.07 - -0.01 m; g = 0.84; 95% CI 0.23 – 1.57). All within group comparisons of jump height between baseline and post-test are presented in FIGURE 8-4

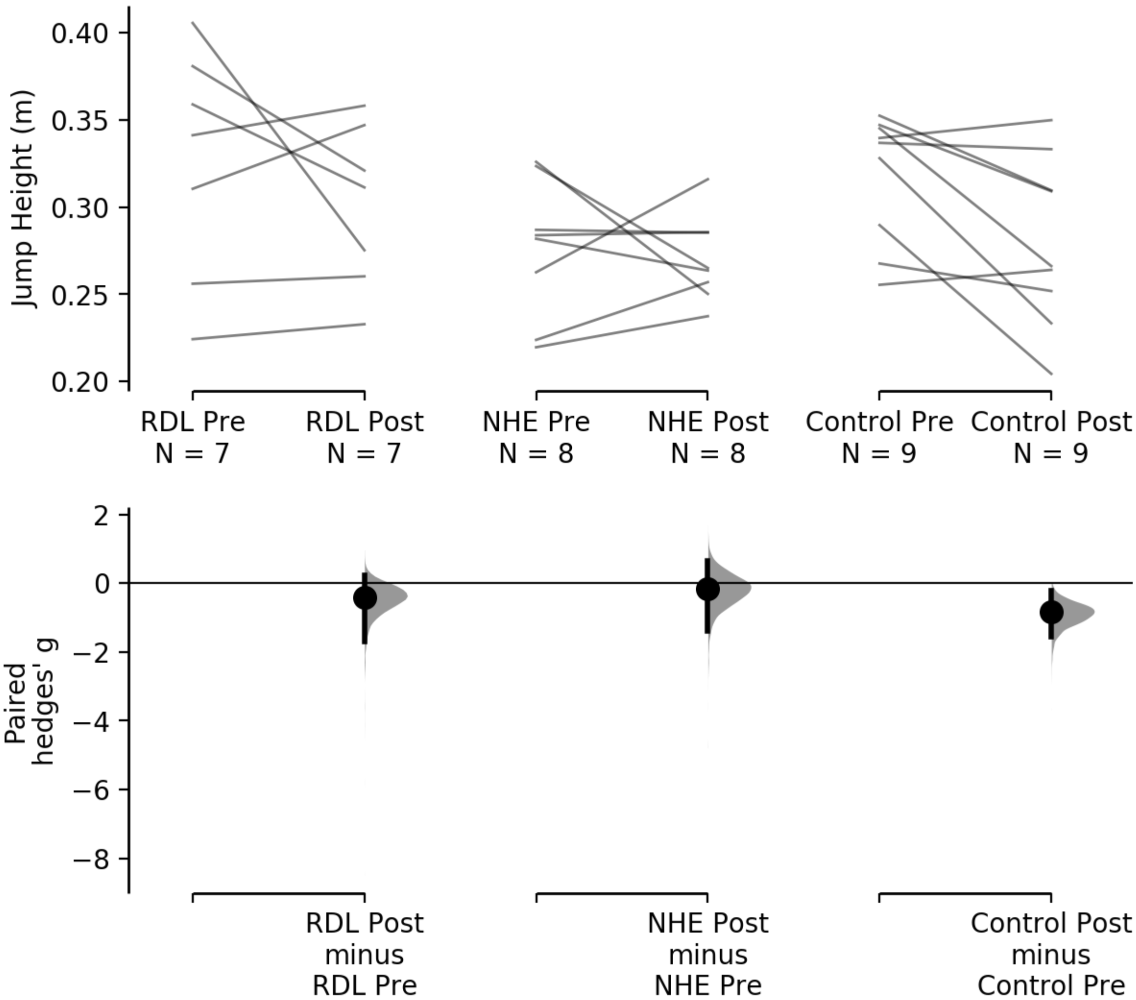


Figure 8-4 The within group pairwise comparisons for CMJ-R Jump Height (m). Individual participant scores are plotted on the upper axes with each paired observation connected by a line. The lower axes show the Hedges g effect size which is depicted as a black dot; 95% Cis of the effect size are indicated by the vertical error bars.

There was no significant main effect for CMJ-R ground contact time (p = 0.627). Within group comparisons showed that there was no significant difference in the RDL group (p = 0.575; mean difference, -6.24 ± 27.83 ms; 95% CI -31.97 – 19.50 ms), which was observed to be a trivial effect (*g* = 0.17; 95% CI -1.03 - 0.41). Similarly, there was no significant within group differences in the NHE group (*p* = 0.825; mean difference, -2.92 ± 28.17 ms; 95% CI -25.84 – 21.26 ms); which was observed as a trivial effect (*g* = 0.07; 95.0% CI -0.61 - 0.56). Finally, there was no significant within group differences in the control group (*p* 0.493; mean difference, 7.48 ± 31.22 ms; 95% CI -16.52 – 31.48 ms), which was observed to be a trivial effect (*g* = 0.16; 95% CI -0.25 – 0.73).

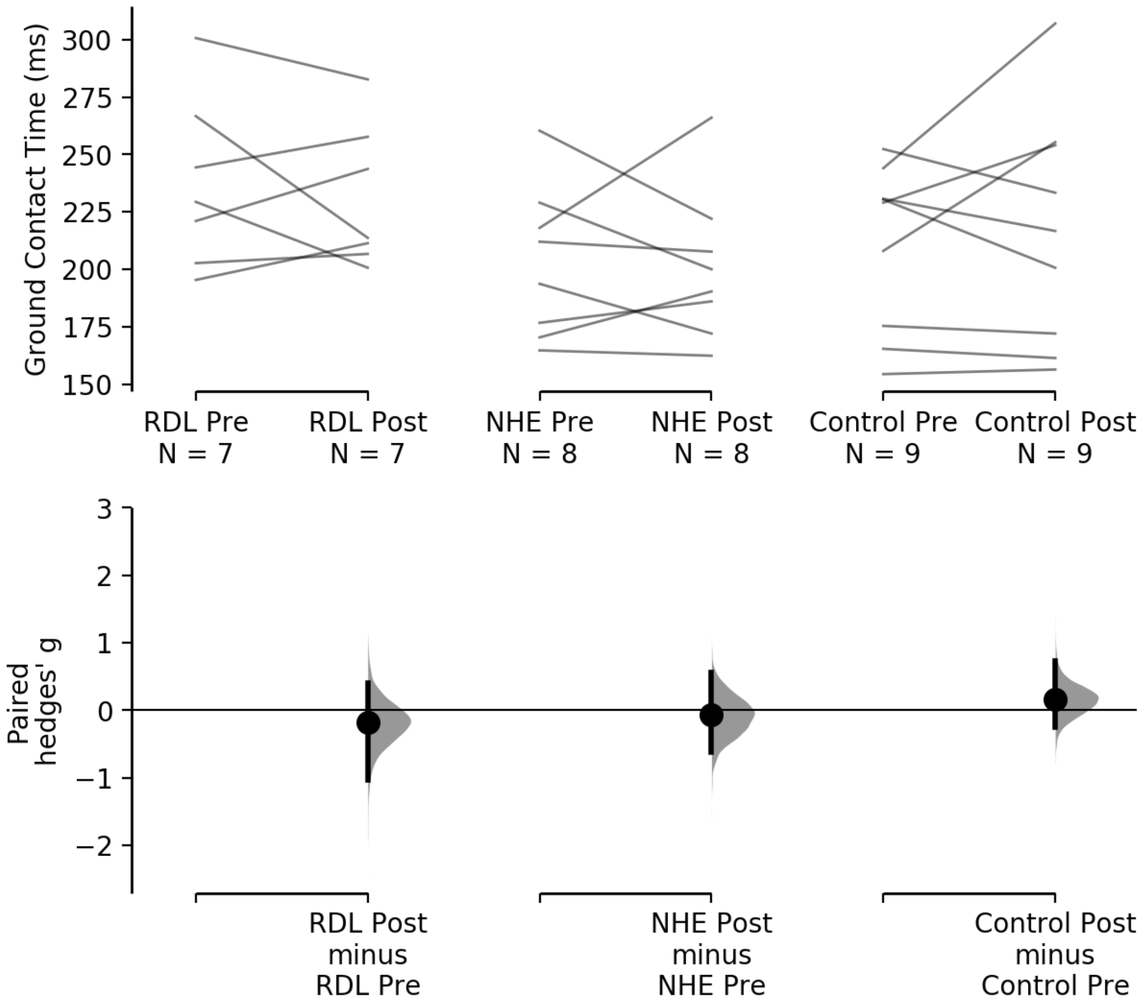


Figure 8-5 The within group pairwise comparisons for CMJ-R Ground Contact Time (ms). Individual participant scores are plotted on the upper axes with each paired observation connected by a line. The lower axes show the Hedges g effect size which is depicted as a black dot; 95% Cis of the effect size are indicated by the vertical error bars.

8.5.4 Isometric Mid-Thigh Pull

For relative net peak force during the IMTP it was observed that one participant from the RDL group (in addition to the six participants from the RDL group that did not complete the IMTP at post-test [TABLE 8-6]), two participants from the NHE and one participant from the control group violated the assumptions of normality for the linear mixed model as the residuals were identified as significant outliers and were therefore removed from the analysis. After the removal of significant outliers, it was observed that there was no significant main effect between groups (*p* = 0.766). Within group comparisons showed that there was no significant difference in the RDL group (*p* = 0.288; mean difference, -3.70 ± 7.5 N.kg; 95% CI -11.60 – 4.30 N.kg), which was small effect, albeit with a very broad 95% confidence interval (*g* = -0.55; 95% CI -1.68 – 0.09). There was no significant difference in the NHE group (*p* = 0.345; mean difference, 1.64; 95% CI -2.20 – 5.47) which was observed to be a small effect (*g* = 0.26; 95% -0.25 – 0.95). Finally, there was no significant difference in the control group (*p* = 0.229; mean difference, 2.70; 95% CI -2.13 – 7.51. which was observed as a moderate effect (*g* = 0.60; 95% CI -0.20 – 1.59).

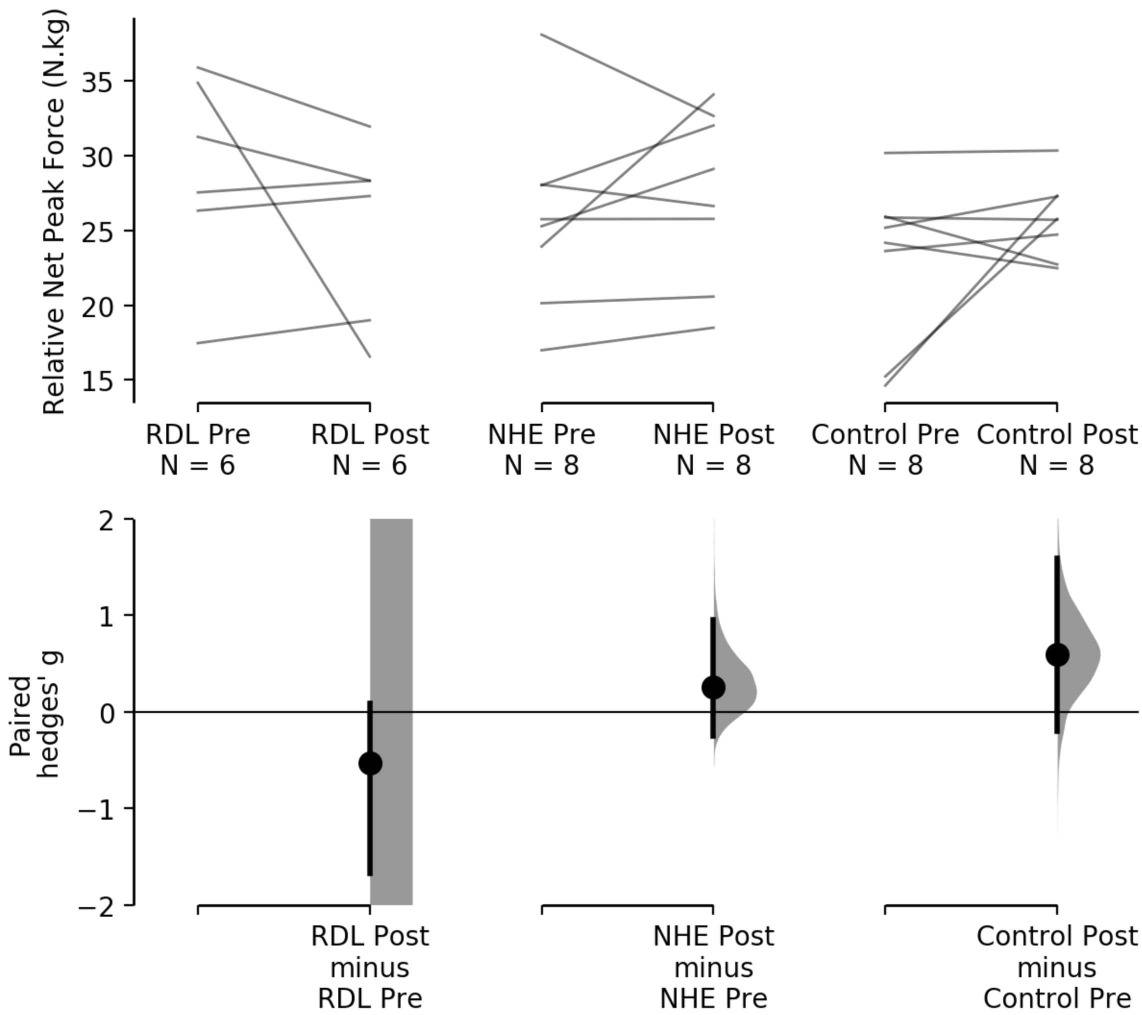


Figure 8-6 The within group pairwise comparisons for IMTP Relative Net Peak Force (N.kg). Individual participant scores are plotted on the upper axes with each paired observation connected by a line. The lower axes show the Hedges g effect size which is depicted as a black dot; 95% Cis of the effect size are indicated by the vertical error bars.

8.5.5 Eccentric Knee Flexor Force

There was a significant main effect for group for relative peak knee flexor force (p = 0.014). Pairwise comparisons showed that again the RDL (mean difference, 0.51 N·kg^{-1}; 95% CI 0.55 – 0.97 N·kg^{-1}; p = 0.030; g 1.04; 95% CI 0.04 – 1.89) and NHE (mean difference, 0.72 N·kg^{-1}; CI 0.24 – 1.18 N·kg^{-1}p = 0.005; g 1.89; 95% CI 1.01 – 2.60)) groups experienced significantly higher change scores compared with the control group. There was no significant difference between RDL and NHE group change scores (mean difference, 0.20 N·kg^{-1}, 95% CI -0.24 – 0.64; *p* = 0.353; *g* = 0.37; 95% CI -0.70 – 1.44).

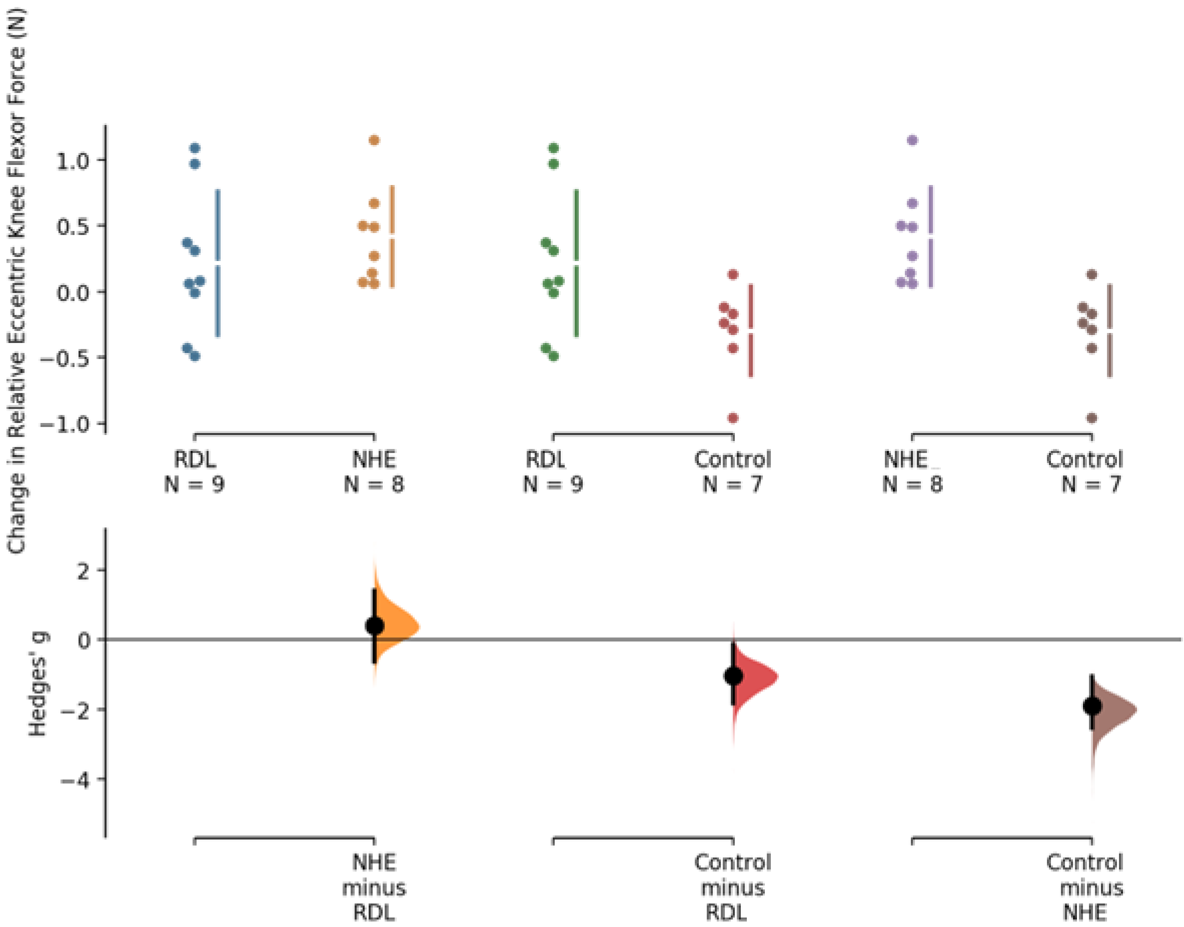


Figure 8-7 Between group pairwise comparisons for relative peak eccentric knee flexor force. Individual participant scores are plotted on the upper axes. The lower axes show the Hedges g effect size which is depicted as a black dot; 95% Cis of the effect size are indicated by the vertical error bars.

Within group comparisons are presented in FIGURE 8-8 and indicate no significant differences in relative eccentric knee flexor force in the RDL (mean difference, 0.21 ± 0.53 N·kg; 95% CI, -0.20 – 0.61; *p* 0.269; *g*, 0.33, 95% CI, -0.18 - 1.3) and control (mean difference, -0.19 ± 0.40 N·kg; 95% CI, -0.56 – 0.19; *p*, 0.269; *g*, -0.15; 95% CI, -0.64 - 0.05) groups, with significant-small improvements in the NHE group (mean difference, 0.40 ± 0.33; 95% CI, 0.12 – 0.68; *p*, 0.012; *g*, 0.46; 95% CI, 0.12 – 1.39).

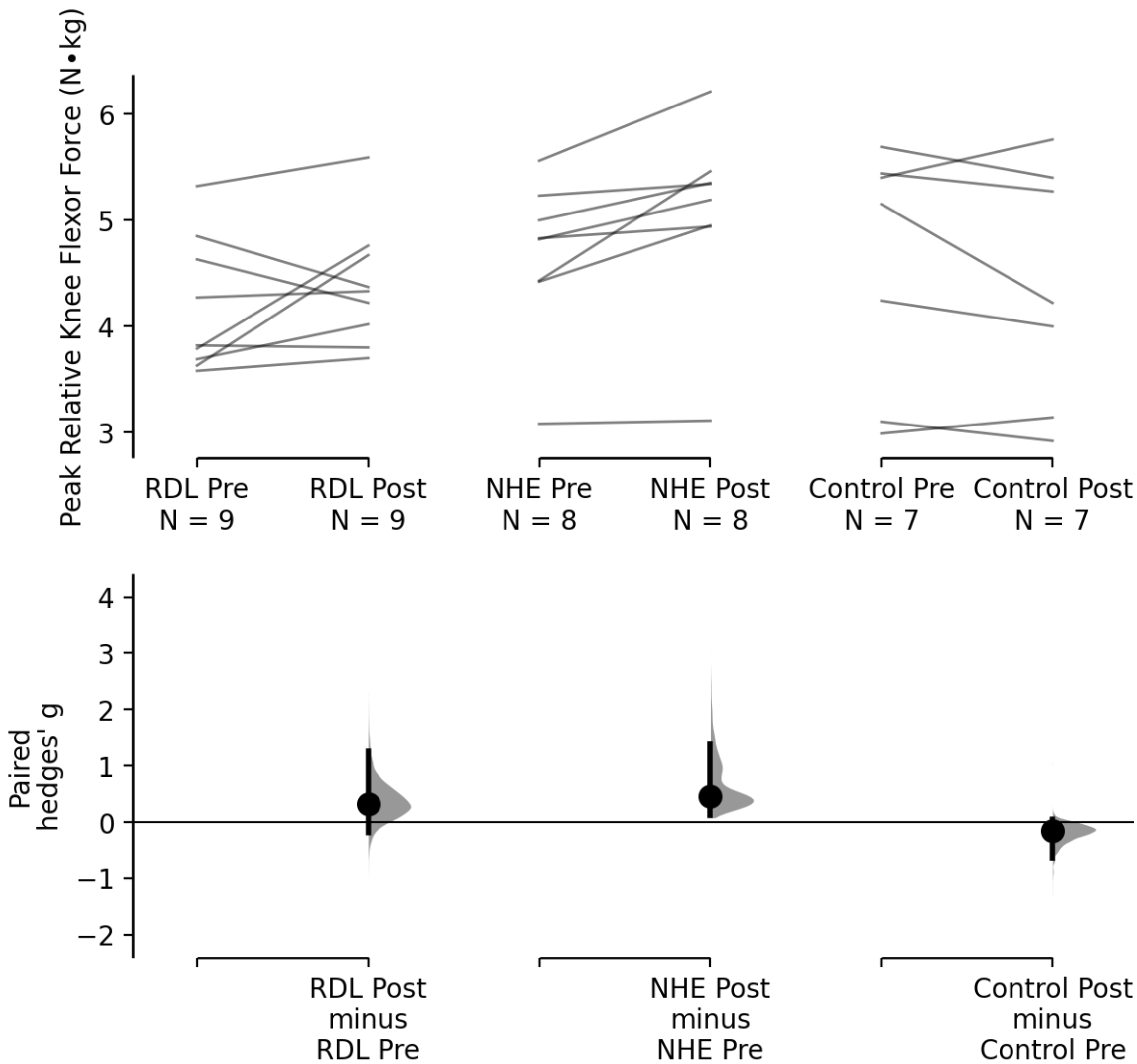


Figure 8-8 The within group pairwise comparisons for relative eccentric knee flexor force. Individual participant scores are plotted on the upper axes with each paired observation connected by a line. The lower axes show the Hedges g effect size which is depicted as a black dot; 95% Cis of the effect size are indicated by the vertical error bars.

8.5.6 Sprint Performance

There was a significant main effect (p = 0.040) for group in 20 m sprint time. Individual pairwise comparisons showed that there was a significant-moderate difference between the NHE and control groups (mean difference, -0.13 s; SE 0.05; p = 0.014; 95% CI -0.23 - -0.03 g =1.14; 95% CI 0.11 – 2.07). There were no significant differences between the RDL and NHE (mean difference -0.05 s; SE 0.50; 95% CI -0.06 – 0.15 s; p = 0.375; g = -0.43; 95% CI -1.26 – 0.46) and RDL and control groups (mean difference, 0.87; SE 0.05; 95% CI -0.01 – 0.18; *p* = 0.077; *g* = 0.71; 95% CI - 0.14 – 1.44).

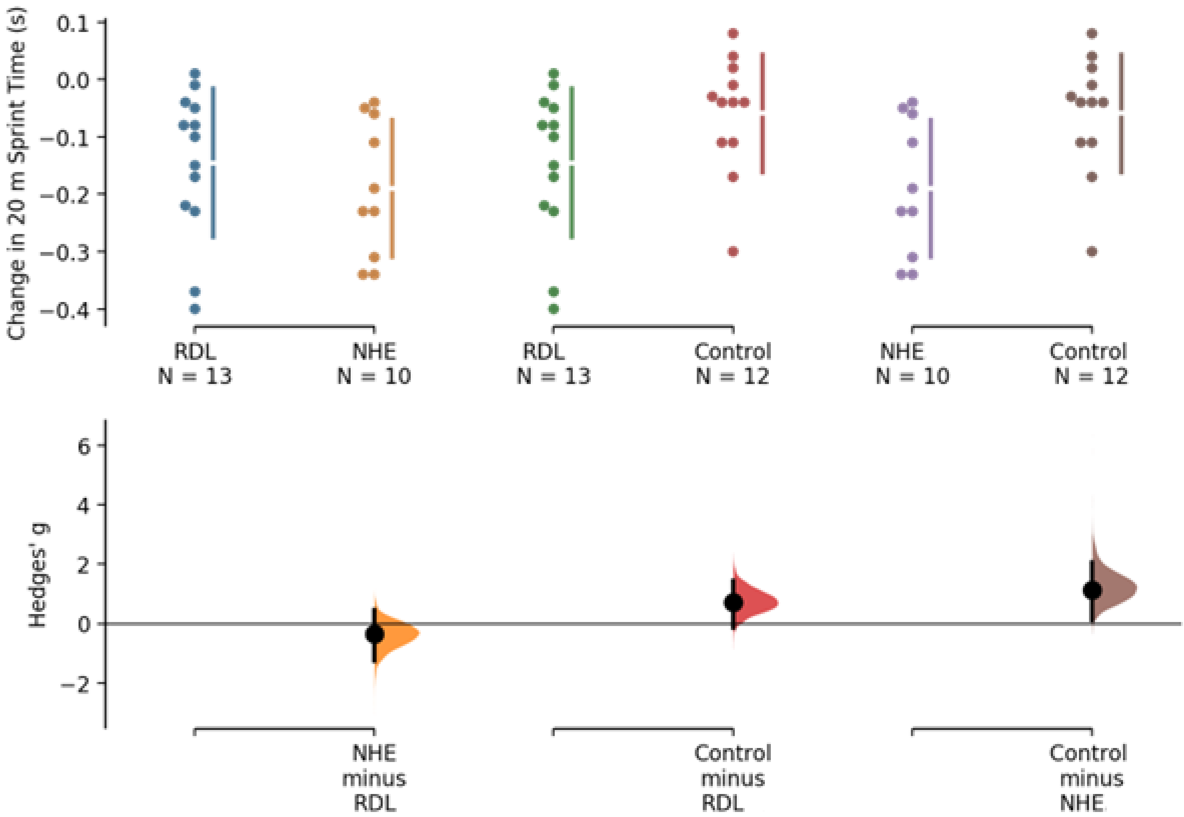


Figure 8-9 The between group pairwise comparisons for change in 20 m sprint time. Individual participant scores are plotted on the upper axes. The lower axes show the Hedges g effect size which is depicted as a black dot; 95% Cis of the effect size are indicated by the vertical error bars.

Individual within-group Wilcoxon signed ranks tests showed (FIGURE 8-8) that there was a significant-moderate (*p* = 0.002; 95% CI -0.06 - -0.22 s *g* = 1.09; 95% CI 0.71 - 0.15)) reduction in 20 m sprint time in the RDL group. There was a significant-large (*p* = 0.005; 95% CI CI -0.05 - -0.53 s; *g* = 1.44*;* 95% 0.90 – 2.06) reduction in 20 m sprint time in the NHE group. However, there was no significant (*p* = 0.054; *g* = 0.46; 95% CI 0.05 – 0.94) difference in post-test scores in the control group compared with baseline.

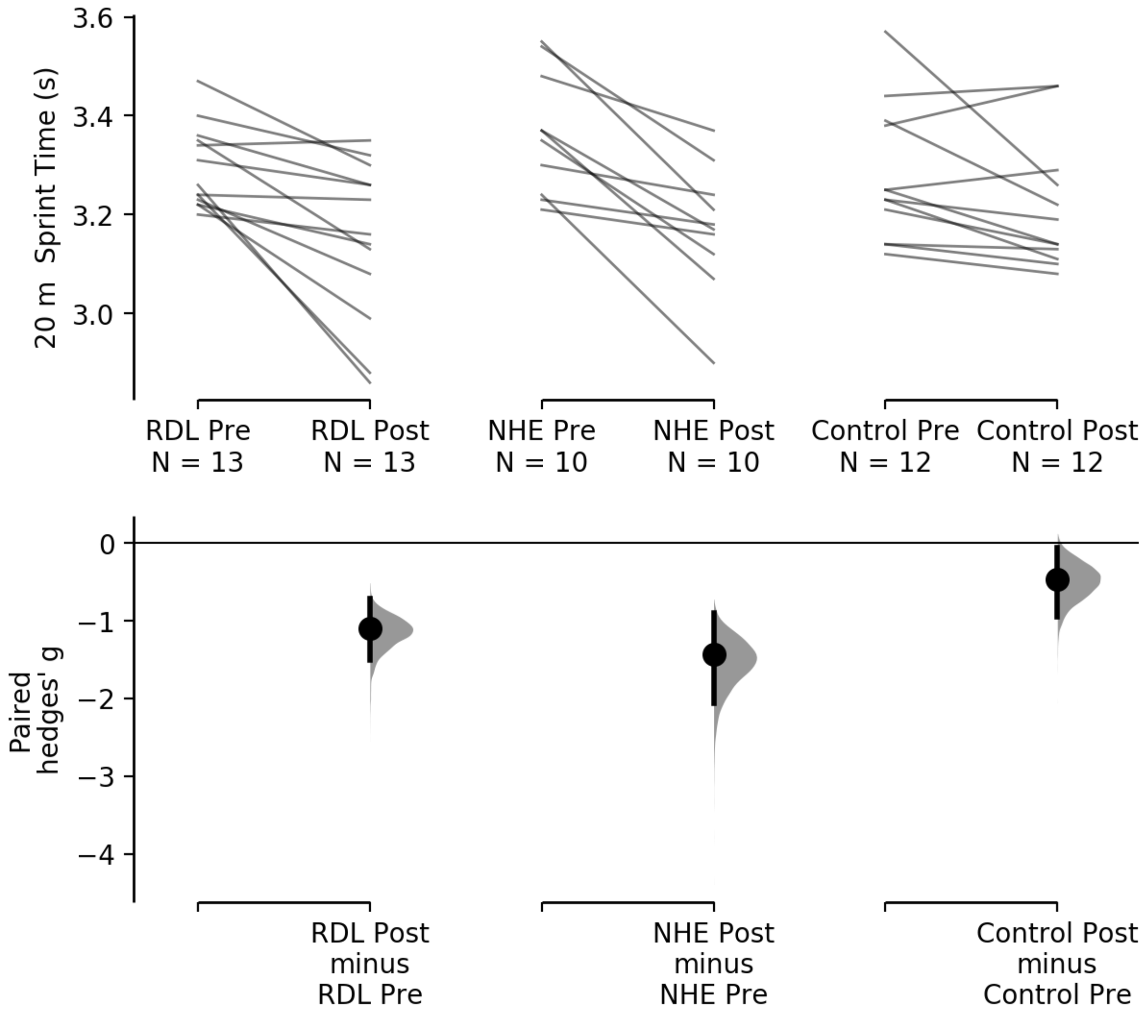


Figure 8-10 The within group pairwise comparisons for 20 m sprint time. Individual participant scores are plotted on the upper axes with each paired observation connected by a line. The lower axes show the Hedges g effect size which is depicted as a black dot; 95% Cis of the effect size are indicated by the vertical error bars.

There was no significant main effect for group for 0-5 m sprint time (p = 0.291). However, individual within group comparisons showed that there was a significant-moderate reduction in 0 – 5 m (FIGURE 8-10) sprint time in the RDL group from baseline to post-test (mean difference, -0.09 ± 0.10 s; 95% CI -0.15 - -0.02; g = -0.87; 95% CI -0.41 - -1.54). There was a significant reduction in 5 m sprint time in the NHE group, (mean difference, -0.14 ± 0.14 s; p = 0.010; 95% CI, -0.23 - - 0.04 s; g = -1.14, 95% CI, -1.85 - -0.49). There was a significant reduction in 5 m sprint time in the control group (mean difference, -0.06 ± 0.09 s; p = 0.028; 95% CI = -0.12 - -0.01 s; g = -0.73; 95% CI = -0.98 - -0.16).

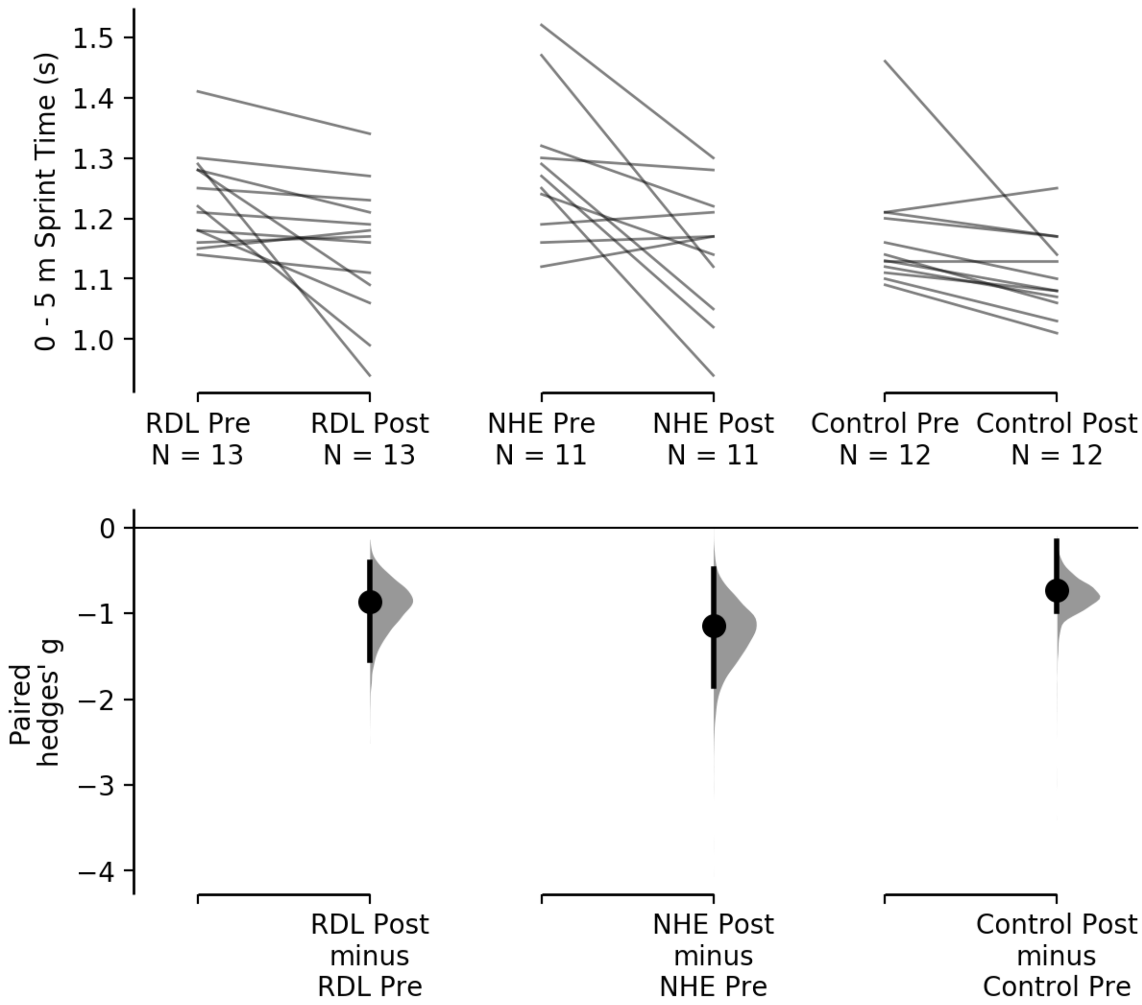


Figure 8-11 The within group pairwise comparisons for 0 - 5 m sprint time. Individual participant scores are plotted on the upper axes with each paired observation connected by a line. The lower axes show the Hedges g effect size which is depicted as a black dot; 95% Cis of the effect size are indicated by the vertical error bars.

There was no significant main effect for group for 5-10 m sprint time (p = 0.455). Individual within group comparisons showed that there was no significant changes between baseline and post-test performance in any of the groups (TABLE 8-11).

Table 8-11 Within group differences between baseline and post-test scores for 5 – 10 m sprint time. Baseline and post-test scores are presented as means (±) with uncertainty of estimates expressed as 95% confidence intervals of the mean difference, magnitude of effect is expressed as Hedges g with associated 95% confidence intervals.

Group	Baseline (s)	Post-Test (s)	95% CI (s)	*p*	*g* (95% CI)
RDL	0.89 (± 0.22)	0.75 (± 0.03)	-0.27 - 0.01	0.058	-0.82 (-0.5 - -1.36)
NHE	0.76 (± 0.04)	0.75 (±0.02)	-0.04 - 0.01	0.447	-0.32 (-1.28 - 0.41)
Control	0.80 (±)0.09)	0.80 (±0.09)	-0.02 - 0.22)	0.704	0.04 (-0.47 - 0.54)

8.6 Discussion

The results of the current study indicate that ecologically valid combined resistance and curvelinear HSR training are effective in enhancing maximal 20 m sprint performance, however programmes including the NHE seem to be superior in also eliciting significant increases in relative eccentric knee flexor strength, relative mean propulsive force and RSImod during the CMJ. Specifically, the NHE experienced significant and large (p = 0.035; g = 1.37) positive adaptation in relative mean propulsive force during the CMJ compared with the RDL group and significant and moderate ($p \leq 0.001$; g = 1.08) positive adaptations in RSImod compared with non-significant and small-moderate adaptation in the RDL and control groups ($p \geq 0.05$; g = -0.36 – 0.68, respectively). With respect to relative peak knee flexor force, there was no significant differences between adaptations in the RDL and NHE groups, however positive adaptations in comparison to the control group were significant and large in the NHE group (p = 0.005; g = 1.89) compared with significant and moderate in the RDL group (p = 0.030; g = 1.04).

As a result, the initial hypothesis that the NHE group would experience the greatest developments in eccentric knee flexor strength was accepted, whereas the subsequent hypotheses that the RDL group would elicit superior increases in lower body strength, sprint and jump performance was rejected. The current study offers an original contribution to knowledge as, to the author's knowledge, this is the first study to compare combined resistance and curvelinear training with either a hip hinge or NHE bias for the mitigation of HSI risk and development of athletic performance.

The NHE group was the only group to experience positive changes in mean propulsive force during the CMJ, however it must be noted here that the mean difference was smaller than the MDD. Two participants from the RDL group and one participant from the Control were removed from the LMM as they were identified as outliers (hence only 6 and 8 observations, respectively), which does indicate underpowering of the comparisons. Similarly, only the NHE group experienced significant and meaningful (p = 0.001; g = 1.08; >MDD) improvements in RSImod during the CMJ. While no outliers were removed from the CMJ RSImod analysis, some participants from each group failed to complete the test due to training commitments with the first-team squad (5 RDL; 2 NHE; and 4 Control). While changes in RSImod in the RDL group did not reach the threshold for statistical significance, the 95% CI of the effect size and the spread of the associated relative likelihood line (represented by the grey shading adjacent to the 95% CI of the effect size in FIGURE 8-3) should be considered, due to the small sample size. Given the small sample at CMJ post-test, it is likely that the observed mean sample in the current study may not be truly representative of the population mean (Cumming, 2007). While the lower bound of the 95% CI of the effect size indicates a moderate negative change in RSImod, the upper 95% CI of the effect size indicates a large positive change in RSImod. Furthermore, given that the visual representation of the relative likelihood line in FIGURE 8-3 indicates that it should not be concluded that the training programme completed by the RDL group does not lead to positive changes in RSImod, but does indicate that a larger sample would be required to more confidently support the potential for positive change.

A likely reason for the difference in adaptation between the NHE and RDL groups is the difference in resistance training intensity, particularly through weeks one to three. For the entirety of the resistance programme, the NHE received two weekly supramaximal eccentric hamstring sessions (with participants instructed to add additional external load in increments of 2.5 kg if they were able to complete a full range of motion NHE), whereas the RDL group started training at 75% of 1 RM which progressed to 87% 1 RM in week four. The reason for this was two-fold. Firstly, there was a lack of a clear and consistent approach to resistance training at the club prior to the commencement of the project, therefore it was not possible to ensure that all participants in the RDL group were accustomed to training with near maximal loads in that exercise. Therefore, to minimise negative responses to training such as DOMS or the potential for musculoskeletal injury from an acute spike in training load associated with a technically challenging exercise (Gabbett et al., 2016; Behan et al., 2023; Hackney et al., 2008), it was decided that an incremental approach to load progression would be adopted. Secondly, to promote true ecological validity of the programmes it was decided that the exercise volumes should be representative of those used in applied practice. As a result, it was deemed that three sets of five repetitions for the RDL (with the aim of progressing to 87% 1 RM) was appropriate, whereas a single set of four repetitions (to achieve eight weekly repetitions) was both ecologically valid and appropriate to achieve a low volume supramaximal stimulus. Additionally, due to the need to reschedule the post test, the RDL missed one of the planned 87% 1 RM sessions, meaning that they only had five sessions at that volume-load, whereas the NHE received eleven sessions that included the NHE.

The NHE is inherently supramaximal in nature, which makes for direct volume-load matching with other exercises difficult. For instance, to achieve a supramaximal eccentric stimulus during the RDL would require the use of weight releasers. Alternatively, a safety bar to be set at the end of the lowering phase so that the eccentric component could be loaded to a level greater than 1 RM which could also be achieved through performing the concentric phase as a conventional deadlift followed by the lowering phase in the manner of an RDL.

While the higher number of completed high-load resistance training sessions by the NHE group may be one reason for greater adaptations in eccentric knee flexor strength, 20 m sprint performance and jump performance, other factors may also have influenced these findings. Firstly, it has been previously observed through surface EMG (Bourne et al., 2018) that the medial hamstrings experience preferential muscle excitation during the NHE compared with the BFLH. Bourne et al. (2018) also reported significant-moderate increases in T2 relaxation time in the semitendinosus compared with the BFLH following the NHE ($p \leq 0.05$; $g = 0.90$), although no significant differences were reported between the semimembranosus and BFLH ($p \geq 0.05$; $g = 0.01$). Further, Yanagisawa and Fukutani (2020) also reported greater contribution of the ST to knee flexion activities than the other hamstring muscles through fMRI. Therefore, the specific NHE training may have elicited superior gains in medial hamstring strength in the NHE group which may then have provided an advantage to that group given that eccentric knee flexor strength was assessed through a NHE. However, given the comparable levels of neuromuscular excitation in the BFLH and medial hamstrings during linear sprint running (Filter et al., 2020), it seems more likely that the differences in adaptations between groups in the current study is mostly attributed to the greater exposure to supramaximal eccentric efforts in the NHE group, indicating that supramaximal eccentric training combined with curvelinear HSR is effective in eliciting positive adaptations in eccentric knee flexor strength and athletic performance.

While the purpose of the current study was to compare combined HSR training with resistance training that included either a hip hinge or NHE focus, the study of Ripley et al. (2023) the effects of adding either NHE or sprint training to an ecologically valid resistance training programme. Ripley et al. (2023) reported adaptations in eccentric knee flexor strength, CMJ performance (take-off velocity and mean propulsive force) and lower body strength (IMTP) greater than those observed in the current study. There may be several explanations for these observations. Firstly, the NHE group in the study of Ripley et al. (2023) included both the NHE and the RDL rather than just one or the other as in the current study, which may therefore indicate additional benefits of including both exercises into a programme. Additionally, the intervention period of Ripley et al. (2023) was 7-weeks in duration as opposed to the 5.5 weeks in the current study. Both studies were limited to only pre-post measures, so it is not possible to calculate dose-response based on comparable training durations, but it is plausible that the longer duration in Ripley et al. (2023) served to further augment adaptations to training. Finally, the baseline relative eccentric knee flexor scores in the NHE group in Ripley et al. (2023) are comparable to both intervention groups in the current study, whereas the sprint group in Ripley et al. (2023) were 28.4% and 40.3% weaker than the RDL and NHE groups in the current study, respectively. This weaker baseline score in the sprint group of Ripley et al. (2023) may partly explain the greater adaptations in that group compared to those in the current study, however the larger increases in strength and jump performance in the control group of Ripley et al. (2023)

would indicate that the resistance programme that included both the NHE and RDL was superior to the programmes in the current study.

Freeman et al. (2019) also reported significant-small increases in eccentric knee flexor strength in both training interventions following a four-week NHE vs sprint training programme. While it was reported that the training programme (four-weeks) was shorter than the programme in the current study, the participants in the study of Freeman et al. (2019) did complete two weeks of ‘familiarisation’ (four sessions) training prior to the four-week intervention. The sprint training used in the familiarisation sessions was 2x40 m at 95% of perceived maximal velocity, progressing to 98%. The familiarisation sessions in the NHE group were 1x1 NHE at 70%, 80% and 90% of perceived maximal intensity followed by 1x3 NHEs at 100% perceived intensity. Given the variability of perceived intensity training it would be impossible to quantify if the supposed submaximal repetitions were truly representative of the intended intensities and it is feasible that adaptations may still have occurred from such submaximal efforts. Unfortunately. Freeman et al. (2019) only took pre and post training measures of strength and performance, so it is not possible to assess the effects of the familiarisation period. As a result, the study of Freeman et al. (2019) was both of longer duration and higher volume than the intervention in the current study. While Freeman et al. (2019) reported larger adaptations in eccentric knee flexor strength than those in the current study, neither intervention group in the Freeman et al. (2019) study experienced any significant changes in maximal velocity running performance, indicating superior adaptations from the lower volume curvelinear running programme used in the current study. Further, Sencese et al. (2023) reported significant improvements in eccentric knee flexor torque in their sprint and NHE training groups, however the magnitude of effect would indicate that while there was small increased from pre-post, any group*time interactions were trivial.

Marchiori et al. (2022) is the only other existing study to directly compare adaptations to NHE vs RDL resistance training. The findings of the current study were consistent with those of Marchiori et al. (2022) in that there was no significant difference in adaptations in eccentric knee flexor strength between RDL and NHE groups. However, in terms of CMJ performance the results of the current study indicated superior adaptations in the NHE over the RDL group in both mean propulsive force and RSImod, whereas Marchiori et al. (2022) observed only trivial changes in CMJ height, but significant-small increases in CMJ height in the RDL group. These differences in adaptation between Marchiori et al. (2022) and the current study may be attributable to the differences in training volume, given the high volumes of NHEs used by Marchiori et al. (2022) (two weekly sessions of four sets of twelve repetitions by week four), which may have led to a lack of high intensity repetitions or lack of progressive overload. On the other hand, the differences in findings may also be attributable to the different methods used to quantify jump performance. Marchiori et al. (2022) only investigated CMJ jump height, which can be influenced by jump strategy and therefore may be questionable as to whether height alone is a sensitive enough measure to assess training adaptations (Morin et al., 2019). The inclusion of a more robust approach to jump analysis used in the current study likely provides a more comprehensive insight into training adaptation.

Adaptations in 20 m sprint performance were also superior in the current study to those in Ripley et al. (2023) Mendiguchia et al. (2020) and Sancese et al. (2023) with moderate and large (>MDD) differences in the RDL and NHE groups, respectively in the current study, compared with small differences in both intervention groups in

Ripley et al. (2023) and in the sprint group in Mediguchia et al. (2020) and no significant change reported by Sencese et al. (2023). These results would indicate superior adaptations in HSR performance from the interventions in the current study which may be attributable to either the specific progressive acceleration element of the HSR sessions in the current study, or the curvelinear nature of the HSR sessions compared with the purely linear nature in Ripley et al. (2023). At baseline, participants in the current study were on average, 6.8% slower than those in Sancese et al. (2023), which may partly explain the superior adaptations if participants in the current study had more scope to improve. However, participants in the current study were, on average, 5.6% and 0.99% faster at baseline than those in Mendiguchia et al. (2020) and Ripley et al. (2023), which seemingly contradicts the notion that the superior adaptations here can be attributed to baseline differences alone. Additionally, these results offer support for a lower total volume of HSR training given that the current programme used one set of four repetitions across all training weeks, whereas Ripley et al. (2023) progressed to seven repetitions in weeks four to seven. Additionally, the intensity of the HSR sessions gradually increased through the reduction of acceleration and deceleration zones in the current study, while only volume increased in Ripley et al. (2023). Therefore, while both programmes may be effective in improving 20 m sprint performance, practitioners may wish to consider the addition of progressive acceleration and deceleration zones either side of a 25 m maximal velocity zone to promote greater adaptations.

Interestingly, while 20 m sprint times were improved to a greater extent in the current study than in Ripley et al. (2023) there were no significant improvements in 0 – 10 m performance in the current study, whereas Ripley et al. (2023) reported small improvements across 0 – 10 m. While there were no significant changes in 5 – 10 m sprint performance in the current study, there was significant-moderate improvements in 5 m sprint performance. Ripley et al. (2023) did not report 5 m sprint performance, so it is not possible to directly compare the mechanisms by which acceleration performance may have been improved across their study and the current study, however it seems that both programmes can be effective in eliciting small-moderate improvements in acceleration. Mendiguchia et al. (2020) also reported positive improvements in 5 m acceleration performance compared with those in the current study, the changes in performance in the study of Mendiguchia et al. (2020) were only possibly small in the NHE group and likely moderate in the sprint group. This finding along with the larger magnitude of 20 m sprint performance in the current study indicate that the acceleration and curvelinear sprinting drills in the current study yielded a more beneficial effect than the programme in Mendiguchia et al. (2020) This may be a noteworthy finding for applied practitioners given that the sprinting programme used in the current study would likely be less time consuming and be less reliant on additional equipment such as sleds and bumper plates due to the supplementary acceleration drills in the programme of Mendiguchia et al. (2020) (e.g., wall accelerations, 70% body weight sled sprints) and the addition of calf specific (albeit using relatively low loads of between 10-70% body weight) resistance training. Furthermore, Freeman et al. (2019) reported non-significant-trivial changes in acceleration and maximum speed in their eccentric training group with significant-moderate improvements in maximum speed, but non-significant-trivial changes in acceleration performance in the sprinting group, which would support the use of the shorter and lower volume sprint training used in the current study.

In the current study, a significant adaptation may have occurred, possibly linked to the enhancement of technical sprinting ability. Previous research, such as that conducted by Morin et al. (2012), has emphasised the importance of orienting the ground reaction force vector more horizontally during sprint running, suggesting that this aspect might be a more critical factor influencing sprint performance than the sheer magnitude of applied force. Consequently, it's noteworthy that only the NHE group displayed positive adaptations in CMJ performance, specifically in relative mean propulsive force. In contrast, none of the groups demonstrated improvements in CMJ-R or IMTP performance. However, both intervention groups did experience positive changes in relative eccentric knee flexor strength and sprint performance. This leads to the hypothesis that while participants may not have enhanced their vertical force application, their ability to generate higher magnitudes of horizontal force and/or orientate the ground reaction force vector more horizontally during sprinting could account for the key adaptations observed in response to the current training intervention.

Unfortunately, during the sprint testing the author did not obtain any kinematic data which could have allowed for technique analysis (e.g., changes in forward lean of the torso or knee drive during the first 5 m) and data collection in a pitch-based setting did not allow for obtaining ground reaction force data. While the available published literature into adaptations to sprint training is still relatively sparce, future studies could consider the use of kinematic and kinetic analyses to better establish the underpinning mechanisms by which improved sprint performance is achieved in response to programmes such as that used in the current study.

8.7 Limitations

While the current study provides some valuable insight into the potential adaptation to combined training methods, it is not without its limitations. Firstly, the duration of the training intervention was shorter than originally planned due to the need to rearrange the final testing day due to UK rail strikes. This change to the planned programme resulted in the loss of the final heavy (87% 1 RM) RDL session which may have contributed to differences in adaptation between the RDL and NHE group. Additionally, this change in schedule had an impact on the number of participants that completed all of the post-test measures. Some participants had been invited to take part in first-team training on the same day as the post-tests. Given that some of the participants were in the final year of their scholarship with the club, it is understandable that they may have prioritised team training to maximise their opportunity at achieving a professional playing contract. Nevertheless, the fact that some participants did not complete the post-test strength or jump tests has led to some underpowering of the statistical analyses in those variables.

It is also clear that the presence of significant outliers in the data set have reduced the statistical power, particularly in the analysis of mean propulsive force for the CMJ, which is further confounded by the significant increase in mean propulsive force in the NHE being smaller than the smallest detectable difference which does question the meaningfulness of this observation.

As per TABLE 8-7 the reliability and absolute variability of the IMTP measures were moderate and unacceptable, respectively, which contributed to a large SEM and very large SDD. In a systematic review by Grgic et al. (2021) it was reported that ICC values for the IMTP typically range from good-excellent (0.730 – 0.990) with a median %CV of 4.9%, which is clearly preferable to the reliability and %CV reported here. The inclusion of a familiarisation session for all testing methods on a separate day to the pre-test may have improved reliability and variability of such measures. Typically, between IMTP trials, the tester would ensure that there is a ≤ 250 N difference between each trial to reduce the risk of erroneous results (Comfort et al. 2019). This was not adhered to in the current study due to testing a large number of athletes in a short period of time. Therefore, ensuring that this threshold was adhered to would likely have improved the reliability of IMTP measures, instead only the best two trials were included for analysis.

Similarly, there was no set threshold for a maximum ground contact time between the first and second jump during the CMJ-R testing. While research into standardisation of CMJ-R testing procedures is currently lacking, as are normative values for CMJ-R performance in soccer, the use of a threshold of ≤ 250 ms may have been useful here to ensure a fast stretch-shortening cycle is utilised across all repetitions.

Additionally, most participants were not familiar with the jump shrug and the hamstring catch which required additional technical coaching from the primary investigator. Therefore, future studies could include the use of familiarisation training sessions, as was the case in Freeman et al. (2019) however should also include additional participant testing between pre-test and the end of familiarisation to account for any adaptations that may occur from the familiarisation sessions.

Finally, it was the intention in the original study proposal to also include assessment of BFLH muscle architecture. (Unfortunately, this was not possible due to off-campus insurance reasons. As a result, ultrasound measures of muscle architecture were not included which does limit understanding of the extent to which the training interventions may have had on muscle architecture as a modifiable risk of HSI.

8.8 Conclusion

The current study aimed to investigate the effects of combined HSR and resistance training with either a knee flexor or hip hinge bias on knee flexor strength, lower limb strength, jump and sprint performance. The programmes included in the current study were designed to be ecologically valid in-line with common training practices as outlined in CHAPTERS 3-4. The findings of the current study indicate that HSR training including curvelinear running and progressive acceleration and deceleration intensities coupled with a resistance training programme that includes the NHE is effective in improving eccentric knee flexor strength, CMJ performance and 20 m sprint performance to a greater magnitude that programmes that do not include the NHE or include the RDL as a substitute for the NHE. However, considering the findings of the current study alongside the existing literature may indicate that the curvelinear HSR programme used in the current study combined with resistance training that includes both the NHE and RDL within the resistance training programme (alongside squat and ballistic movements) may be more effective. It is also recommended that future training intervention studies include familiarisation prior to baseline testing sessions to improve reliability and absolute variability, particularly of measures of lower limb strength. Additionally, to ensure that all study participants are competent in the performance of all exercises included in a training intervention, researchers should consider the use of a familiarisation training period but should also quantify any adaptations that may have taken place due to such familiarisation sessions.

Chapter 9 Thesis Summary and Recommendations for Future Research

8.1 Summary and Conclusions

The overarching aim of the current thesis was to inform exercise selection principles, athlete assessment, and training practices for mitigating HSI risk factors and improving markers of athletic performance. The aims were achieved firstly through exploring the applied practices, and training perceptions of applied practitioners, followed by establishing reliable means of EMG amplitude normalisation to inform a more biomechanically robust exercise comparison of commonly used hip-hinge based exercises that was previously lacking in the literature. Further, the reliability and force-time characteristics of the NHE were established, given their commonality in applied practice. Finally, the findings of the qualitative chapters, exercise comparisons and means of reliably assessing hamstring strength using the NHE were applied to develop an ecologically valid training programme that compared adaptations from combined resistance and HSR training including either a knee flexor or hip hinge bias.

In CHAPTERS 3 and 4, it was found that practitioners do tend to utilise lower volumes of the NHE than were recommended in the early literature from the likes of Mjølsnes et al. (2004), but perhaps not as low as the 8 weekly repetitions that may be sufficient to elicit positive adaptations (Cuthbert et al. 2019). Further, it was evident that practitioners, unsurprisingly, do not use single exercise interventions for the development of hamstring strength, which raises questions about the ecological validity of the majority of training intervention studies. Similarly, it was unsurprising that practitioners utilise combined resistance training with HSR, despite very little available empirical evidence in relation to expected adaptations to such training. There was a large amount of variance in the thresholds that practitioners used to define 'high speed' and ‘sprint’ running. While most practitioners that took part in CHAPTERS 3 and 4, tended to utilise higher HSR and sprint running thresholds than the studies reviewed by Freeman et al. (2022), the fact that some of those published studies that were reviewed, used thresholds as low as 40% and 58% of maximum velocity to define HSR and sprinting, respectively. Therefore, it was concluded that there was a need to develop more empirical evidence into adaptations to combined HSR and resistance training to help practitioners to better understand adaptations beyond single exercise interventions and beyond resistance-only training.

It was also established from CHAPTERS 3 and 4 that practitioners value the use of the hip-hinge as a resistance training stimulus that is viewed as potentially more ‘functional’ than the NHE. Therefore, CHAPTER 5 aimed to establish the most reliable means of EMG amplitude normalisation for gluteal and hamstring muscles to enable exercise comparison between two commonly used hip-hinge based exercises in CHAPTER 6. It was established that a manual resistance during a hip extension effort allowed for acceptable reliability. This method was then used along estimations of hip and knee joint moments to compare the RDL and GM to inform potential adaptations to training. The two exercises performed at 5 RM loads were found to be largely similar with the exception of significantly larger hip extensor moments in the first 7% and last 15% of normalised time in the RDL, which may lead to higher potential for the development of hip extensor strength. It was identified in CHAPTERS 3 and 4 that the NordBord is commonly used in practice to quantify knee flexor strength. Therefore, it was decided that the NordBord would also be used in CHAPTER 8 to monitor adaptations to training. As the previously reported reliability of the Nordic device was based on a prototype with a higher sampling frequency than the commercially available model, the reliability of the commercial device was established in CHAPTER

7. Reliability of the NordBord was found to be acceptable, but the removal of the first of multiple repetitions was found to improve reliability and was therefore recommended for future use.

Finally, an ecologically valid combined training programme was investigated in CHAPTER 8. This chapter aimed to investigate A) the effects of combined resistance and HSR training on markers of HSI risk and athletic performance and B) investigate any potential differences in adaptations when the resistance programme contained either a hip-hinge or knee flexor bias. It was concluded that both training interventions were effective in eliciting meaningful adaptations in knee flexor strength and 20 m sprint performance, however adaptations from a programme including the NHE may be superior than in those that do not include it. Both intervention groups and the control group experienced positive adaptations in 5 m sprint performance, which may indicate that the curvelinear running programme used is sufficient to improve acceleration performance, however the addition of an eccentrically bias hamstring training element is needed to also elicit adaptations in 20 m sprint performance.

9.2 Limitations and Recommendations for Future Research

The thesis is, of course, not without its limitations. First, the sample for the training intervention study was limited by several factors. The primary factor was that the original schedule for post-testing had to be changed due to railway strikes. The testing day had to be moved forward as the following week was scheduled to be the academy's spring break, meaning that several participants would not be able to attend testing, and the removal of the training stimulus for two-weeks would likely have resulted in some loss of positive adaptations that may have occurred (Timmins et al. 2016). Therefore, the testing day was moved to an earlier point in the week which caused a clash with first-team training. As many of the participants were in final year scholarships, some were invited to take part in first team training to assist with final decisions on those that may be offered first year professional contracts. The club's first-team trained on a separate facility to the academy so while some participants were able to do elements of the post-test, such as the sprints, as part of their warm-up, and some participants did return to the academy facility after first-team training to take part in testing, there were several participants that failed to do so. Further, some participants in certain tests (e.g., CMJ-R and IMTP) violated the assumptions of normal distribution. This could have been controlled with more stringent standardisation of testing. For instance, it has been recommended that between trial variance of ≤250 N (Comfort et al. 2019) should be maintained during the IMTP. Also, it could be argued that the ground contact time between the first and second jumps in the CMJ-R should be ≤250 ms to be representative of a fast stretch shortening cycle, however longer ground contact of 350 ms have been reported in the limited existing CMJ-R literature (Xu et al. 2023). Due to the nature of testing a large squad of athletes as well as the added pressures of the rearranged schedule and participants wanting to leave to attend first-team training, these recommendations were not adhered to. In a more ideal testing environment, a higher standard of testing standardisation and quality control may have mitigated these violations in normal distribution.

Adaptations eccentric knee flexor strength, CMJ (take-off velocity and mean propulsive force) and lower body strength (IMTP) reported by Ripley et al. (2023) were greater than those in the current study. The longer training intervention used by Ripley et al. (2023) may, in part, explain these differences. However, participants used by Ripley et al. (2023) were weaker at baseline than those used in the current thesis and may therefore have also had more scope for improvement. Furthermore, both the NHE and sprint programmes used by Ripley et al. (2023) included the RDL. Adaptations in 20 m sprint performance were in the current thesis were superior to those reported by Ripley et al. (2023), Mendiguchia et al. (2022) and Sancese et al. (2023) with moderate and large (>MDD) differences in the RDL and NHE groups, respectively in the current thesis. Therefore, it seems logical that combined HSR and resistance training programmes including both the RDL and low volumes of the NHE should be advocated.

It should also be noted that there were some examples of negative responders to the training. For example, in the RDL group, two participants were weaker in relative knee flexor force at post-test, despite no change in body mass. This is an important observation as any training programme that elicits negative adaptations should not be considered to be valid. Prior to commencing the study, the participants participated in what was described by their coaching staff as “some gym work”, but there was no clear structure or indication of training experience. Some participants indicated that they did use NHEs in their programme prior to the study, but this was not quantified. Therefore, there is a potential that some of the participants did use NHEs in their programme prior to the study, and that the removal of such a supramaximal eccentric stimulus could have led to negative adaptations. Further to this, it was not feasible to accurately quantify training loads outside of the intervention programmes (e.g., GPS derived monitoring of pitch-based training or match-play) due to a lack of resources. Therefore, it is not known whether some participants had experienced higher total training volumes prior to the testing days than others, or if those participating in first-team training had experienced acute spikes in overall training loads which may have influenced testing.

From the practitioner surveys and interviews, it was clear that S&C practitioners tend to give high priority to technique and movement competence during their athlete training sessions as opposed to focusing on volume-loads. From a practical perspective, a lot of time in the first two to three weeks of the programme in CHAPTER 8 was spent on coaching technique, particularly in the hip-hinge and jump shrug. Therefore, to further promote ecological validity of future studies, researchers should incorporate a familiarisation period similar to that used by Freeman et al. (2019). In doing so, researchers could assess baseline performance, utilise a three to four week familiarisation block in which priority is given to movement competency. At this point an additional testing point could control for any adaptations or learning effect that may have taken place in response to familiarisaiton, before then conducting a combined training intervention similar to that used in the current thesis. Designing a study in this way would likely allow for better controlling of learning effects and ensure more scope for progression of absolute loads used in the programme itself.

The exercise comparison presented in CHAPTER 6 developed the basis for hip-hinge based exercise selection beyond EMG alone as was the case in the likes of Zebis et al. (2013), McAllister et al. (2014) and Vigotsky et al. (2015) by providing estimations of hip and knee joint moments during the eccentric and concentric phases of the GM and RDL. While estimations of joint moments with EMG likely allow for a better understanding of potential adaptations to training over EMG alone, more computationally advanced methods to estimate muscle force contributions are available (Van Hooren et al. 2022). Future researchers should continue to develop the knowledge base around muscle force contributions to exercises, however an interesting observation not fully explored by the current thesis can be made from FIGURES 6-6; 6-8. Here it is clear to see that the EMG amplitude increases towards the end of the eccentric phase, which is likely to generate muscle force for deceleration of downwards movement in order to transition to the concentric phase. However, what is not yet known is whether this increase in excitation is also accompanied by the start of fascicle shortening, which could mean that the concentric phase actually starts while the bar is still being lowered toward the ground. Chumanov et al. (2011) reported that the hamstrings underwent negative work up between 50-90% of the HSR cycle (swing phase), but positive work in the final 10%, preceding the stance phase. Future research allowing for synchronous capture of ultrasound imaging along with estimations of joint moments and muscle force contributions investigate whether the increase in muscle excitation at the end of the eccentric phase in the current thesis, is also associated with a transition to positive work and fascicle shortening prior to what is currently termed the end of the eccentric phase.

From a philosophical perspective, the findings of the current thesis highlight the intricate balance between empirical evidence, practical application, and the broader understanding of strength and conditioning. By delving into practitioners' training perceptions and conducting empirical research, the results of this thesis highlight the necessity of a symbiotic relationship between theory and practice. The chapters presented here bridge the gap between scientific inquiry and real-world application, demonstrating that successful training interventions are not solely dependent on singular exercise interventions but on a nuanced integration combined of training modalities to mitigate injury risk and develop athletic performance.

Moreover, this thesis invites a broader reflection on the nature of evidence-based practice in strength and conditioning. It challenges the ecological shortcomings of existing literature on single exercise interventions, advocating for more ecologically valid research approaches that better reflect the complexities of actual training environments. This perspective is crucial, as it acknowledges that the journey to enhancing performance and mitigating injury risks is not linear but requires an adaptive, holistic approach. The findings support a paradigm shift towards integrating diverse training stimuli, emphasising the importance of ongoing empirical inquiry to refine and validate these integrative practices. This philosophical viewpoint enriches the discourse in strength and conditioning, advocating for a dynamic and responsive framework in training methodologies.

9.3 Practical Applications

Strength and Conditioning practitioners do utilise evidence-based recommendations for the use of the NHE, contrary to previous claims (Bahr et al. 2015). Although practitioners do reduce overall NHE volumes in-season, compared with off-season, there is evidence from the current thesis, Ripley et al. (2013) and Cuthbert et al. (2020) that there is likely scope for these volumes to be even lower but still elicit positive adaptations. Further, practitioners use a multitude of resistance-based and running based training methods to mitigate risks of HSI and develop athletic, performance, but the relative thresholds used in applied practice are likely higher than what has been previously investigated (Freeman et al. 2022), but that the results here and by Ripley et al. (2023) indicate that positive and meaningful adaptations in athletic performance and risk factor mitigation can be achieved through combined resistance training with progressive maximal intensity running.

Practitioners looking to implement hip-hinge based training in their programmes should select the RDL based on the findings here and by Ripley et al. (2023). There is no evidence from here or Marchiori et al. (2022) that the RDL elicits positive adaptations over the NHE and therefore the two should be used in conjunction as was the case in Ripley et al. (2023). CHAPTER 5 in the current thesis indicates that there is a potential that the GM may elicit similar adaptations to the RDL but at lower absolute loads, but this requires further investigation.

In terms of future researchers that wish to conduct EMG-based exercise comparisons of the hamstring or gluteal muscles, the manual resistance during prone lying hip extension method seems the most appropriate, however it should be noted that the lack of correlation between EMG amplitude and isokinetic derived torque remains a limitation of EMG given that recorded amplitude may not be truly representative of an individual's maximal force or torque generating capacity.

When using the NordBord to make assessments of eccentric knee flexor strength, the commercially available device is associated with acceptable levels of reliability and absolute variability for peak force. However, when making assessments of mean force, the removal of the first of multiple repetitions can improve reliability. Further to this, future athlete benchmarking using the NordBord may benefit from the use of force analysis across the entire force-time curve as a means of investigating between-limb asymmetries. However, given that the magnitude and direction of between limb asymmetries is highly variable, this should be conducted on an individual basis rather than assessments made on mean values across an entire cohort.

References

AFL Doctors Association, & AFL Physiotherapists Association. (2016). 2016 AFL injury survey. *AFL Operations Department,*

Al Attar, W. S. A., Soomro, N., Sinclair, P. J., Pappas, E., & Sanders, R. H. (2017). Effect of injury prevention programs that include the nordic hamstring exercise on hamstring injury rates in soccer players: A systematic review and meta-analysis. *Sports Medicine (Auckland, N.Z.), 47*(5), 907–916. 10.1007/s40279-016-0638-2

Albertus-Kajee, Y., Tucker, R., Derman, W., & Lambert, M. (2010). Alternative methods of normalising EMG during cycling. *Journal of Electromyography and Kinesiology, 20*(6), 1036–1043. 10.1016/j.jelekin.2010.07.011

Allen, T., Taberner, M., Zhilkin, M., & Rhodes, D. (2024). Running more than before? the evolution of running load demands in the English premier league. *International Journal of Sports Science & Coaching, 19*(2), 779–787. 10.1177/17479541231164507

Allen, T. J., Leung, M., & Proske, U. (2010). The effect of fatigue from exercise on human limb position sense. *The Journal of Physiology, 588*(8), 1369–1377. 10.1113/jphysiol.2010.187732

Allison, G. T., Marshall, R. N., & Singer, K. P. (1993). EMG signal amplitude normalization technique in stretch-shortening cycle movements. *Journal of Electromyography and Kinesiology, 3*(4), 236–244. 10.1016/1050-6411(93)90013-M

Alonso-Fernandez, D., Docampo-Blanco, P., & Martinez-Fernandez, J. (2018). Changes in muscle architecture of biceps femoris induced by eccentric strength training with Nordic hamstring exercise. *Scandinavian Journal of Medicine & Science in Sports, 28*(1), 88–94. 10.1111/sms.12877

Alonso, J., McHugh, M. P., Mullaney, M. J., & Tyler, T. F. (2009). Effect of hamstring flexibility on isometric knee flexion angle-torque relationship. *Scandinavian Journal of Medicine & Science in Sports, 19*(2), 252–256. 10.1111/j.1600-0838.2008.00792.x

Alt, T., Nodler, Y. T., Severin, J., Knicker, A. J., & Strüder, H. K. (2018). Velocity-specific and time-dependent adaptations following a standardized nordic hamstring exercise training. *Scandinavian Journal of Medicine & Science in Sports, 28*(1), 65–76. 10.1111/sms.12868

Altmann, S., Forcher, L., Ruf, L., Beavan, A., Groß, T., Lussi, P., Woll, A., & Härtel, S. (2021). Match-related physical performance in professional soccer: Position or player specific? *PloS One, 16*(9), e0256695. 10.1371/journal.pone.0256695

Andersen, V., Pedersen, H., Fimland, M. S., Shaw, M., Solstad, T. E. J., Stien, N., Cumming, K. T., & Saeterbakken, A. H. (2021). Comparison of muscle activity in three single-joint, hip extension exercises in resistance-trained women. *Journal of Sports Science & Medicine, 20*(2), 181–187. 10.52082/jssm.2021.181

Árnason, S., Árnason, S., Birnir, B., Birnir, B., Guðmundsson, T., Guðmundsson, T., Guðnason, G., Guðnason, G., Briem, K., & Briem, K. (2014). Medial hamstring muscle activation patterns are affected 1–6 years after ACL reconstruction using hamstring autograft. *Knee Surgery, Sports Traumatology, Arthroscopy, 22*(5), 1024–1029. 10.1007/s00167-013-2696-4

Askling, C., Karlsson, J., & Thorstensson, A. (2003). Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scandinavian Journal of Medicine & Science in Sports, 13*(4), 244–250. 10.1034/j.1600-0838.2003.00312.x

Askling, C. M., Tengvar, M., Saartok, T., & Thorstensson, A. (2008). Proximal hamstring strains of stretching type in different sports. *The American Journal of Sports Medicine, 36*(9), 1799–1804. 10.1177/0363546508315892

Askling, C. M., Tengvar, M., Saartok, T., & Thorstensson, A. (2007a). Acute first-time hamstring strains during slow-speed stretching. *The American Journal of Sports Medicine, 35*(10), 1716–1724. 10.1177/0363546507303563

Askling, C. M., Malliaropoulos, N., & Karlsson, J. (2012). High-speed running type or stretching-type of hamstring injuries makes a difference to treatment and prognosis. *British Journal of Sports Medicine, 46*(2), 86. 10.1136/bjsports-2011-090534

Askling, C. M., Tengvar, M., Saartok, T., & Thorstensson, A. (2007b). Acute first-time hamstring strains during high-speed running. *The American Journal of Sports Medicine, 35*(2), 197–206. 10.1177/0363546506294679

Askling, C. M., Tengvar, M., Tarassova, O., & Thorstensson, A. (2014). Acute hamstring injuries in swedish elite sprinters and jumpers: A prospective randomised controlled clinical trial comparing two rehabilitation protocols. *British Journal of Sports Medicine, 48*(7), 532–539. 10.1136/bjsports-2013-093214

Askling, C. M., Tengvar, M., & Thorstensson, A. (2013). Acute hamstring injuries in swedish elite football: A prospective randomised controlled clinical trial comparing two rehabilitation protocols. *British Journal of Sports Medicine, 47*(15), 953–959. 10.1136/bjsports-2013-092165

Bahr, R., Thorborg, K., & Ekstrand, J. (2015). Evidence-based hamstring injury prevention is not adopted by the majority of champions league or norwegian premier league football teams: The nordic hamstring survey. *British Journal of Sports Medicine, 49*(22), 1466–1471. 10.1136/bjsports-2015-094826

Baroni, B., Ruas, C., Ribeiro-Alvares, J., & Pinto, R. (2020). Hamstring-to-quadriceps torque ratios of professional male soccer players: A systematic review. *Journal of Strength and Conditioning Research, 34*(1), 281–293. 10.1519/JSC.0000000000002609

Barrué-Belou, S., Démaret, M., Wurtz, A., Ducloux, A., Fourchet, F., & Bothorel, H. (2024). Absolute and normalized normative torque values of knee extensors and flexors in healthy trained subjects: Asymmetry questions the classical use of uninjured limb as reference. *Arthroscopy, Sports Medicine, and Rehabilitation, 6*(1), 100861. 10.1016/j.asmr.2023.100861

Bautista, I. J., Vicente-Mampel, J., Baraja-Vegas, L., Segarra, V., Martín, F., & Van Hooren, B. (2021). The effects of the nordic hamstring exercise on sprint performance and eccentric knee flexor strength: A systematic review and meta-analysis of intervention studies among team sport players. *Journal of Science and Medicine in Sport, 24*(9), 931–938. 10.1016/j.jsams.2021.03.009

Behan, F. P., Opar, D. A., Vermeulen, R., Timmins, R. G., & Whiteley, R. (2023a). The dose–response of pain throughout a nordic hamstring exercise intervention. *Scandinavian Journal of Medicine & Science in Sports, 33*(4), 542–546. 10.1111/sms.14317

Behan, F. P., Opar, D. A., Vermeulen, R., Timmins, R. G., & Whiteley, R. (2023b). The dose–response of pain throughout a nordic hamstring exercise intervention. *Scandinavian Journal of Medicine & Science in Sports, 33*(4), 542–546. 10.1111/sms.14317

Bennell, K. L., & Crossley, K. (1996). Musculoskeletal injuries in track and field: Incidence, distribution and risk factors. *Australian Journal of Science and Medicine in Sport, 28*(3), 69. https://www.ncbi.nlm.nih.gov/pubmed/8937661

Bennell, K., Wajswelner, H., Lew, P., Schall-Riaucour, A., Leslie, S., Plant, D., & Cirone, J. (1998). Isokinetic strength testing does not predict hamstring injury in australian rules footballers. *British Journal of Sports Medicine, 32*(4), 309–314. 10.1136/bjsm.32.4.309

Benoit, D. L., Lamontagne, M., Cerulli, G., & Liti, A. (2003). The clinical significance of electromyography normalisation techniques in subjects with anterior cruciate ligament injury during treadmill walking. *Gait & Posture, 18*(2), 56–63. 10.1016/S0966-6362(02)00194-7

Beuchat, A., & Maffiuletti, N. A. (2019). Foot rotation influences the activity of medial and lateral hamstrings during conventional rehabilitation exercises in patients following anterior cruciate ligament reconstruction. *Physical Therapy in Sport, 39*, 69–75. 10.1016/j.ptsp.2019.06.010

Bezerra, E. S., Simao, R., Fleck, S. J., Paz, G., Maia, M., Costa, P. B., Amadio, A. C., Miranda, H., & Serrao, J. C. (2013). Electromyographic activity of lower body muscles during the deadlift and still-legged deadlift. *Journal of Exercise Physiology Online, 16*(3), 30.

Bishop, C., Turner, A., Gonzale-Skok, O., & Read, P. (2020). Inter-limb asymmetry during rehabilitation: Understanding formulas and monitoring the "magnitude" and "direction".

. *Sports Medicine Journal, 9*, 18–22.

Bloomfield, J., Polman, R., & O'Donoghue, P. (2007). Physical demands of different positions in FA premier league soccer. *Journal of Sports Science & Medicine, 6*(1), 63–70. https://www.ncbi.nlm.nih.gov/pubmed/24149226

Bolgla, L. A., & Uhl, T. L. (2007). Reliability of electromyographic normalization methods for evaluating the hip musculature. *Journal of Electromyography and Kinesiology, 17*(1), 102–111. 10.1016/j.jelekin.2005.11.007

Boltz, A., Wait, J., Cheatham, S., O’Connell, R., Chandran, A., & Hooper, N. (2022). Poster 190: Epidemiology of hamstring tears in NCAA sports: 2014/15-2018/19. *Orthopaedic Journal of Sports Medicine, 10*(7_suppl5), 2325967121. 10.1177/2325967121S00751

Boren, K., Conrey, C., Le Coguic, J., Paprocki, L., Voight, M., & Robinson, T. K. (2011). Electromyographic analysis of gluteus medius and gluteus maximus during rehabilitation exercises. *International Journal of Sports Physical Therapy, 6*(3), 206–223. https://www.ncbi.nlm.nih.gov/pubmed/22034614

Bourne, M., Opar, D., Williams, M., & Shield, A. (2015). Eccentric knee-flexor strength and hamstring injury risk in rugby union: A prospective cohort study. *Journal of Science and Medicine in Sport, 19*, e73. 10.1016/j.jsams.2015.12.177

Bourne, M. N., Bruder, A. M., Mentiplay, B. F., Carey, D. L., Patterson, B. E., & Crossley, K. M. (2019). Eccentric knee flexor weakness in elite female footballers 1–10 years following anterior cruciate ligament reconstruction. *Physical Therapy in Sport, 37*, 144–149. 10.1016/j.ptsp.2019.03.010

Bourne, M. N., Duhig, S. J., Timmins, R. G., Williams, M. D., Opar, D. A., Al Najjar, A., Kerr, G. K., & Shield, A. J. (2017a). Impact of the nordic hamstring and hip extension exercises on hamstring architecture and morphology: Implications for injury prevention. *British Journal of Sports Medicine, 51*(5), 469–477. 10.1136/bjsports-2016-096130

Bourne, M. N., Opar, D. A., Williams, M. D., & Shield, A. J. (2015). Eccentric knee flexor strength and risk of hamstring injuries in rugby union. *The American Journal of Sports Medicine, 43*(11), 2663–2670. 10.1177/0363546515599633

Bourne, M. N., Williams, M. D., Opar, D. A., Al Najjar, A., Kerr, G. K., & Shield, A. J. (2017b). Impact of exercise selection on hamstring muscle activation. *British Journal of Sports Medicine, 51*(13), 1021. 10.1136/bjsports-2015-095739

Bowen, L., Gross, A. S., Gimpel, M., Bruce-Low, S., & Li, F. (2020). Spikes in acute:Chronic workload ratio (ACWR) associated with a 5–7 times greater injury rate in english premier league football players: A comprehensive 3-year study. *British Journal of Sports Medicine, 54*(12), 731–738. 10.1136/bjsports-2018-099422

Boyatzis, R. E. (1998). *Transforming qualitative information: Thematic analysis and code development : Pbk*. Sage Publications.

Bramah, C., Mendiguchia, J., Dos'Santos, T., & Morin, J. (2024). Exploring the role of sprint biomechanics in hamstring strain injuries: A current opinion on existing concepts and evidence. *Sports Medicine (Auckland), 54*(4), 783–793. 10.1007/s40279-023-01925-x

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101. 10.1191/1478088706qp063oa

Brian T. Feeley, Steve Kennelly, Ronnie P. Barnes, Mark S. Muller, Bryan T. Kelly, Scott A. Rodeo, & Russell F. Warren. (2008). Epidemiology of national football league training camp injuries from 1998 to 2007. *The American Journal of Sports Medicine, 36*(8), 1597–1603. 10.1177/0363546508316021

Brooks, J. H. M., Fuller, C. W., Kemp, S. P. T., & Reddin, D. B. (2005a). Epidemiology of injuries in English professional rugby union: Part 1 match injuries. *British Journal of Sports Medicine, 39*(10), 757–766. 10.1136/bjsm.2005.018135

Brooks, J. H. M., Fuller, C. W., Kemp, S. P. T., & Reddin, D. B. (2005b). Epidemiology of injuries in English professional rugby union: Part 2 training injuries. *British Journal of Sports Medicine, 39*(10), 767–775. 10.1136/bjsm.2005.018408

Brooks, J. H. M., Fuller, C. W., Kemp, S. P. T., & Reddin, D. B. (2005c). A prospective study of injuries and training amongst the England 2003 rugby world cup squad. *British Journal of Sports Medicine, 39*(5), 288–293. 10.1136/bjsm.2004.013391

Brooks, J. H. M., Fuller, C. W., Kemp, S. P. T., & Reddin, D. B. (2006). Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *The American Journal of Sports Medicine, 34*(8), 1297–1306. 10.1177/0363546505286022

Brughelli, M., Mendiguchia, J., Nosaka, K., Idoate, F., Arcos, A. L., & Cronin, J. (2010). Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players. *Physical Therapy in Sport, 11*(2), 50–55. 10.1016/j.ptsp.2009.12.002

Brukner, P., Nealon, A., Morgan, C., Burgess, D., & Dunn, A. (2014). Recurrent hamstring muscle injury: Applying the limited evidence in the professional football setting with a seven-point programme. *British Journal of Sports Medicine, 48*(11), 929–938. 10.1136/bjsports-2012-091400

Buchheit, M., Cholley, Y., Nagel, M., & Poulos, N. (2016). The effect of body mass on eccentric knee-flexor strength assessed with an instrumented nordic hamstring device (nordbord) in football players. *International Journal of Sports Physiology and Performance, 11*(6), 721–726. 10.1123/ijspp.2015-0513

Burden, A. M., Trew, M., & Baltzopoulos, V. (2003). Normalisation of gait EMGs: A re-examination. *Journal of Electromyography and Kinesiology, 13*(6), 519–532. 10.1016/S1050-6411(03)00082-8

Burden, A. (2010). How should we normalize electromyograms obtained from healthy participants? what we have learned from over 25 years of research. *Journal of Electromyography and Kinesiology, 20*(6), 1023–1035. 10.1016/j.jelekin.2010.07.004

Burden, A., & Bartlett, R. (1999). Normalisation of EMG amplitude: An evaluation and comparison of old and new methods. *Medical Engineering & Physics, 21*(4), 247–257. 10.1016/S1350-4533(99)00054-5

Burigo, R. L., Scoz, R. D., Alves, B. M. d. O., da Silva, R. A., Melo-Silva, C. A., Vieira, E. R., Hirata, R. P., & Amorim, C. F. (2020). Concentric and eccentric isokinetic hamstring injury risk among 582 professional elite soccer players: A 10-years retrospective cohort study. *BMJ Open Sport & Exercise Medicine, 6*(1), e000868. 10.1136/bmjsem-2020-000868

Bush, M., Barnes, C., Archer, D. T., Hogg, B., & Bradley, P. S. (2015). Evolution of match performance parameters for various playing positions in the english premier league. *Human Movement Science, 39*, 1–11. 10.1016/j.humov.2014.10.003

Bussey, Melanie D.|Aldabe, Daniela|Adhia, Divya|Mani, Ramakrishnan. (2017). Reliability of surface electromyography activity of gluteal and hamstring muscles during sub-maximal and maximal voluntary isometric contractions. *Musculoskeletal Science and Practice, 34*, 103–107. 10.1016/j.msksp.2017.09.004

Butterfield, T. A., & Herzog, W. (2005). Quantification of muscle fiber strain during in vivo repetitive stretch-shortening cycles. *Journal of Applied Physiology, 99*(2), 593–602. 10.1152/japplphysiol.01128.2004

Cadu, J., Goreau, V., & Lacourpaille, L. (2022). A very low volume of nordic hamstring exercise increases maximal eccentric strength and reduces hamstring injury rate in professional soccer players. *Journal of Sport Rehabilitation, 31*(8), 1061–1066. 10.1123/jsr.2021-0445

Caldbeck, P. (2020). *Contextual sprinting in premier league football* Available from ProQuest One Academic Eastern Edition https://search.proquest.com/docview/2494304314

Chalker, W. J., Shield, A. J., Opar, D. A., & Keogh, J. W. L. (2016). Comparisons of eccentric knee flexor strength and asymmetries across elite, sub-elite and school level cricket players. *PeerJ, 4*, e1594. 10.7717/peerj.1594

Chalker, W. J., Shield, A. J., Opar, D. A., Rathbone, E. N., & Keogh, J. W. L. (2018). Effect of acute augmented feedback on between limb asymmetries and eccentric knee flexor strength during the nordic hamstring exercise. *PeerJ (San Francisco, CA), 6*, e4972. 10.7717/peerj.4972

Chumanov, E. S., Heiderscheit, B. C., & Thelen, D. G. (2007). The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting. *Journal of Biomechanics, 40*(16), 3555–3562. 10.1016/j.jbiomech.2007.05.026

Chumanov, E. S., Schache, A. G., Heiderscheit, B. C., & Thelen, D. G. (2012). Hamstrings are most susceptible to injury during the late swing phase of sprinting. *British Journal of Sports Medicine, 46*(2), 90. 10.1136/bjsports-2011-090176

Clark, R., Bryant, A., Culgan, J., & Hartley, B. (2005). The effects of eccentric hamstring strength training on dynamic jumping performance and isokinetic strength parameters: A pilot study on the implications for the prevention of hamstring injuries. *Physical Therapy in Sport, 6*(2), 67–73. 10.1016/j.ptsp.2005.02.003

Clarke, A. C., Anson, J. M., & Pyne, D. B. (2017). Game movement demands and physical profiles of junior, senior and elite male and female rugby sevens players. *Journal of Sports Sciences, 35*(8), 727–733. 10.1080/02640414.2016.1186281

Collazo García, C., Rueda, J., Suárez Luginick, B., & Navarro, E. (2018). Differences in the electromyographic activity of lower-body muscles in hip thrust variations. *Journal of Strength and Conditioning Research,* , 1. 10.1519/JSC.0000000000002859

Comfort, P., Haff, G. G., Suchomel, T. J., Soriano, M. A., Pierce, K. C., Hornsby, W. G., Haff, E. E., Sommerfield, L. M., Chavda, S., Morris, S. J., Fry, A. C., & Stone, M. H. (2023). National strength and conditioning association position statement on weightlifting for sports performance. *Journal of Strength and Conditioning Research, 37*(6), 1163–1190. 10.1519/JSC.0000000000004476

Comfort, P., Regan, A., Herrington, L., Thomas, C., McMahon, J., & Jones, P. (2017). Lack of effect of ankle position during the nordic curl on muscle activity of the biceps femoris and medial gastrocnemius. *Journal of Sport Rehabilitation, 26*(3), 202–207. 10.1123/jsr.2015-0130

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. (2015). A comparison of gluteus maximus, biceps femoris, and vastus lateralis electromyographic activity in the back squat and barbell hip thrust exercises. *Journal of Applied Biomechanics, 31*(6), 452–458. 10.1123/jab.2014-0301

Croisier, J., Ganteaume, S., Binet, J., Genty, M., & Ferret, J. (2008). Strength imbalances and prevention of hamstring injury in professional soccer players. *The American Journal of Sports Medicine, 36*(8), 1469–1475. 10.1177/0363546508316764

Cumming, G. (2007). Inference by eye: Pictures of confidence intervals and thinking about levels of confidence. *Teaching Statistics, 29*(3), 89–93. 10.1111/j.1467-9639.2007.00267.x

Cuthbert, M., Haff, G. G., McMahon, J. J., Evans, M., & Comfort, P. (2023). Microdosing: A conceptual framework for use as programming strategy for resistance training in team sports. *Strength and Conditioning Journal, Publish Ahead of Print*10.1519/SSC.0000000000000786

Cuthbert, M., Ripley, N., McMahon, J. J., Evans, M., Haff, G. G., & Comfort, P. (2019). The effect of Nordic hamstring exercise intervention volume on eccentric strength and muscle architecture adaptations: A systematic review and meta-analyses. *Sports Medicine (Auckland, N.Z.), 50*(1), 83–99. 10.1007/s40279-019-01178-7

Dalton, S. L., Kerr, Z. Y., & Dompier, T. P. (2015). Epidemiology of hamstring strains in 25 NCAA sports in the 2009-2010 to 2013-2014 academic years. *The American Journal of Sports Medicine, 43*(11), 2671–2679. 10.1177/0363546515599631

Danielsson, A., Horvath, A., Senorski, C., Alentorn-Geli, E., Garrett, W. E., Cugat, R., Samuelsson, K., & Hamrin Senorski, E. (2020). The mechanism of hamstring injuries – a systematic review. *BMC Musculoskeletal Disorders, 21*(1), 641. 10.1186/s12891-020-03658-8

De Luca, C. J., Donald G., Kuznetsov, M., & Roy, S. H. (2010). Filtering the surface EMG signal: Movement artifact and baseline noise contamination. *Journal of Biomechanics, 43*(8), 1573–1579. 10.1016/j.jbiomech.2010.01.027

Debien, P. B., Timoteo, T. F., Gabbett, T. J., & Bara Filho, M. G. (2022). Training-load management in rhythmic gymnastics: Practices and perceptions of coaches, medical staff, and gymnasts. *International Journal of Sports Physiology and Performance, 17*(4), 530–540. 10.1123/ijspp.2021-0279

Delahunt, E., McGroarty, M., De Vito, G., & Ditroilo, M. (2016). Nordic hamstring exercise training alters knee joint kinematics and hamstring activation patterns in young men. *European Journal of Applied Physiology, 116*(4), 663–672. 10.1007/s00421-015-3325-3

Delvaux, F., Schwartz, C., Decréquy, T., Devalckeneer, T., Paulus, J., Bornheim, S., Kaux, J., & Croisier, J. (2020). Influence of a field hamstring eccentric training on muscle strength and flexibility. *International Journal of Sports Medicine, 41*(4), 233–241. 10.1055/a-1073-7809

Ditroilo, M., De Vito, G., & Delahunt, E. (2013). Kinematic and electromyographic analysis of the nordic hamstring exercise. *Journal of Electromyography and Kinesiology, 23*(5), 1111–1118. 10.1016/j.jelekin.2013.05.008

Dobbs, I. J., Oliver, J. L., Wong, M. A., Moore, I. S., & Lloyd, R. S. (2020). Movement competency and measures of isometric and dynamic strength and power in boys of different maturity status. *Scandinavian Journal of Medicine & Science in Sports, 30*(11), 2143–2153. 10.1111/sms.13773

Dobbs, I., Oliver, J., Wong, M., Moore, I., & Lloyd, R. (2020). Effects of a 12-week training program on isometric and dynamic force-time characteristics in pre– and Post–Peak height velocity male athletes. *Journal of Strength and Conditioning Research, 34*(3), 653–662. 10.1519/JSC.0000000000003467

Doherty, T. (2001). The influence of aging and sex on skeletal muscle mass and strength. *Current Opinion in Clinical Nutrition and Metabolic Care, 4*(6), 503–508. 10.1097/00075197-200111000-00007

Dos'Santos, T., Jones, P. A., Kelly, J., McMahon, J. J., Comfort, P., & Thomas, C. (2019). Effect of sampling frequency on isometric midthigh-pull kinetics. *International Journal of Sports Physiology and Performance, 14*(4), 525–530. 10.1123/ijspp.2019-2015-0222

Dos'Santos, T., Jones, P. A., Comfort, P., & Thomas, C. (2017). Effect of different onset thresholds on isometric midthigh pull force-time variables. *Journal of Strength and Conditioning Research, 31*(12), 3463–3473. 10.1519/jsc.0000000000001765

Dragan Radovanovic, Aleksandar Ignjatovic, & Ratko Stankovic. (2007). Influence of strength training program on isometric muscle strength in young athletes. *Acta Medica Medianae, 46*(3), 16–20. https://doaj.org/article/d2281eaf5f0f4b4eacb1a4d6ffc9f5a3

Drezner, J., Ulager, J., & Sennett, B. (2005). Hamstring muscle injuries in track and field athletes: A 3-year study at the penn relay carnival. *Clinical Journal of Sport Medicine, 15*(5), 386. 10.1097/01.jsm.0000186687.28802.df

Duhig, S. J., Bourne, M. N., Buhmann, R. L., Williams, M. D., Minett, G. M., Roberts, L. A., Timmins, R. G., Sims, C. K. E., & Shield, A. J. (2019). Effect of concentric and eccentric hamstring training on sprint recovery, strength and muscle architecture in inexperienced athletes. *Journal of Science and Medicine in Sport, 22*(7), 769–774. 10.1016/j.jsams.2019.01.010

Duncan, M. J., Weldon, A., Barnett, L. M., & Lander, N. (2022). Perceptions and practices of fundamental movement skills in grassroots soccer coaches. *International Journal of Sports Science & Coaching, 17*(4), 761–771. 10.1177/17479541211073547

Ekstrand, J., Hägglund, M., & Waldén, M. (2011). Injury incidence and injury patterns in professional football: The UEFA injury study. *British Journal of Sports Medicine, 45*(7), 553–558. 10.1136/bjsm.2009.060582

Ekstrand, J. (2013). Keeping your top players on the pitch: The key to football medicine at a professional level. *British Journal of Sports Medicine, 47*(12), 723–724. 10.1136/bjsports-2013-092771

Ekstrand, J., Bengtsson, H., Waldén, M., Davison, M., Khan, K. M., & Hägglund, M. (2022). Hamstring injury rates have increased during recent seasons and now constitute 24% of all injuries in men's professional football: The UEFA elite club injury study from 2001/02 to 2021/22. *British Journal of Sports Medicine, 57*(5), 292–298. 10.1136/bjsports-2021-105407

Ekstrand, J., Healy, J. C., Waldén, M., Lee, J. C., English, B., & Hägglund, M. (2012). Hamstring muscle injuries in professional football: The correlation of MRI findings with return to play. *British Journal of Sports Medicine, 46*(2), 112–117. 10.1136/bjsports-2011-090155

Ekstrand, J., Waldén, M., & Hägglund, M. (2016). Hamstring injuries have increased by 4% annually in men's professional football, since 2001: A 13-year longitudinal analysis of the UEFA elite club injury study. *British Journal of Sports Medicine, 50*(12), 731–737. 10.1136/bjsports-2015-095359

Erickson, L. N., & Sherry, M. A. (2017). Rehabilitation and return to sport after hamstring strain injury. *Journal of Sport and Health Science, 6*(3), 262–270. 10.1016/j.jshs.2017.04.001

Evangelidis, P. E., Shan, X., Otsuka, S., Yang, C., Yamagishi, T., & Kawakami, Y. (2023). Fatigue-induced changes in hamstrings' active muscle stiffness: Effect of contraction type and implications for strain injuries. *European Journal of Applied Physiology, 123*(4), 833–846. 10.1007/s00421-022-05104-0

Evangeldis, P., Massey, G., Pain, M. T., & Folland, J. (2015). Biceps femoris aponeurosis size: A potential risk factor for strain injury? *Medicine & Science in Sports & Exercise, 47*(7), 1383–1389. 10.1249/MSS.0000000000000550

Faigenbaum, A. D., McFarland, J. E., Herman, R. E., Naclerio, F., Ratamess, N. A., Kang, J., Myer, G. D. (2012) Reliability of the one-repetition-maximum power clean test in adolescent athletes. Journal of Strength and Conditioning Research 26(2), 432-437. 10.1519/JSC.0b013e318220db2c

Filter, A., Olivares-Jabalera, J., Santalla, A., Morente-Sánchez, J., Robles-Rodríguez, J., Requena, B., & Loturco, I. (2020). Curve sprinting in soccer: Kinematic and neuromuscular analysis. *International Journal of Sports Medicine, 41*(11), 744–750. 10.1055/a-1144-3175

Fiorentino, N. M, Epstein, F. H., & Blemker, S. S. (2011). Activation and aponeurosis morphology affect in vivo muscle tissue strains near the myotendinous junction. *Journal of Biomechanics, 45*(4), 647–652. 10.1016/j.jbiomech.2011.12.015

Fitzpatrick, J. F., Linsley, A., & Musham, C. (2019). Running the curve: A preliminary investigation into curved sprinting during football match-play. *Sports Performance & Science Reports,* , 1–3.

Fousekis, K., Tsepis, E., Poulmedis, P., Athanasopoulos, S., & Vegenas, G. (2010). Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: A prospective study of 100 professional players *45*

Franettovich Smith, M. M., Bonacci, J., Mendis, M. D., Christie, C., Rotstein, A., & Hides, J. A. (2017). Gluteus medius activation during running is a risk factor for season hamstring injuries in elite footballers. *Journal of Science and Medicine in Sport, 20*(2), 159–163. 10.1016/j.jsams.2016.07.004

Freeman, B. W., Talpey, S. W., James, L. P., & Young, W. B. (2021). Sprinting and hamstring strain injury: Beliefs and practices of professional physical performance coaches in australian football. *Physical Therapy in Sport, 48*, 12–19. 10.1016/j.ptsp.2020.12.007

Freeman, B. W., Talpey, S. W., James, L. P., Opar, D. A., & Young, W. B. (2023). Common high-speed running thresholds likely do not correspond to high-speed running in field sports. *Journal of Strength and Conditioning Research, 37*(7), 1411–1418. 10.1519/JSC.0000000000004421

Freeman, B. W., Young, W. B., Talpey, S. W., Smyth, A. M., Pane, C. L., & Carlon, T. A. (2019). The effects of sprint training and the nordic hamstring exercise on eccentric hamstring strength and sprint performance in adolescent athletes. *Journal of Sports Medicine and Physical Fitness, 59*(7), 1119. 10.23736/S0022-4707.18.08703-0

Frounfelter, G. (2000). Teaching the romanian deadlift. *Strength and Conditioning Journal, 22*(2), 55. 10.1519/00126548-200004000-00017

Fyfe, J. J., Opar, D. A., Williams, M. D., & Shield, A. J. (2013). The role of neuromuscular inhibition in hamstring strain injury recurrence. *Journal of Electromyography and Kinesiology, 23*(3), 523–530. 10.1016/j.jelekin.2012.12.006

Gabbe, B. J., Bennell, K. L., Finch, C. F., Wajswelner, H., & Orchard, J. W. (2006a). Predictors of hamstring injury at the elite level of australian football. *Scandinavian Journal of Medicine & Science in Sports, 16*(1), 7–13. 10.1111/j.1600-0838.2005.00441.x

Gabbe, B. J., Branson, R., & Bennell, K. L. (2006b). A pilot randomised controlled trial of eccentric exercise to prevent hamstring injuries in community-level australian football. *Journal of Science and Medicine in Sport, 9*(1), 103–109. 10.1016/j.jsams.2006.02.001

Gabbe, B., Finch, C., Wajswelner, H., & Bennell, K. (2002). Australian football: Injury profile at the community level. *Journal of Science and Medicine in Sport, 5*(2), 149–160. 10.1016/S1440-2440(02)80036-6

Gabbett, T. J., Hulin, B. T., Blanch, P., & Whiteley, R. (2016). High training workloads alone do not cause sports injuries: How you get there is the real issue. *British Journal of Sports Medicine, 50*(8), 444–445. 10.1136/bjsports-2015-095567

Garrett, W. E. (Jan 1, 1996). Muscle strain injuries. Paper presented at the *, 24*(6) S2–S8. 10.1177/036354659602406s02 https://www.ncbi.nlm.nih.gov/pubmed/8947416

George Koulouris, David A. Connell, Peter Brukner, & Michal Schneider-Kolsky. (2007). Magnetic resonance imaging parameters for assessing risk of recurrent hamstring injuries in elite athletes. *The American Journal of Sports Medicine, 35*(9), 1500–1506. 10.1177/0363546507301258

Gérard, R., Gojon, L., Decleve, P., & Van Cant, J. (2020). The effects of eccentric training on biceps femoris architecture and strength: A systematic review with meta-analysis. *Journal of Athletic Training, 55*(5), 501–514. 10.4085/1062-6050-194-19

Green, B., Bourne, M. N., van Dyk, N., & Pizzari, T. (2020). Recalibrating the risk of hamstring strain injury (HSI): A 2020 systematic review and meta-analysis of risk factors for index and recurrent hamstring strain injury in sport. *British Journal of Sports Medicine, 54*(18), 1081–1088. 10.1136/bjsports-2019-100983

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. 10.1177/0363546508314413

Grgic, J., Scapec, B., Mikulic, P., & Pedisic, Z. (2022). Test-retest reliability of isometric mid-thigh pull maximum strength assessment: A systematic review. *Biology of Sport, 39*(2), 407–414. 10.5114/biolsport.2022.106149

Guruhan, S., Kafa, N., Ecemis, Z. B., & Guzel, N. A. (2020). Muscle activation differences during eccentric hamstring exercises. *Sports Health,* , 194173812093864–1941738120938649. 10.1177/1941738120938649

Hackney, K. J., Engels, H., & Gretebeck, R. J. (2008). Resting energy expenditure and delayed-onset muscle soreness after full-body resistance training with an eccentric concentration. *Journal of Strength and Conditioning Research, 22*(5), 1602–1609. 10.1519/JSC.0b013e31818222c5

Haff, G., & Triplett, N. T. (2016). *Essentials of strength training and conditioning* (Fourth edition ed.). Human Kinetics.

Hagel, B. (2005). Hamstring injuries in Australian football. *Clinical Journal of Sport Medicine, 15*(5), 400. 10.1097/01.jsm.0000179227.01404.d3

Hansson G A., Strömberg, U., Larsson, B., Ohlsson, K., Balogh, I., & Moritz, U. (1992). Electromyographic fatigue in neck/shoulder muscles and endurance in women with repetitive work. *Ergonomics, 35*(11), 1341–1352. 10.1080/00140139208967397

Haugen, T., & Buchheit, M. (2016). Sprint running performance monitoring: Methodological and practical considerations. *Sports Medicine, 46*(5), 641–656. 10.1007/s40279-015-0446-0

Haugen, T., Tønnessen, E., Hisdal, J., & Seiler, S. (2014). The role and development of sprinting speed in soccer. *International Journal of Sports Physiology and Performance, 9*(3), 432–441. 10.1123/ijspp.2013-0121

Hawkins, R. D., Hulse, M. A., Wilkinson, C., Hodson, A., & Gibson, M. (2001). The association football medical research programme: An audit of injuries in professional football. *British Journal of Sports Medicine, 35*(1), 43–47. 10.1136/bjsm.35.1.43

Hay, J. G. (1999). Changes in muscle-tendon length during the take-off of a running long jump. *Journal of Sports Sciences, 17*(2), 159–172. 10.1080/026404199366262

Hegyi, A., Péter, A., Finni, T., & Cronin, N. J. (2018). Region-dependent hamstrings activity in Nordic hamstring exercise and stiff-leg deadlift defined with high-density electromyography. *Scandinavian Journal of Medicine & Science in Sports, 28*(3), 992–1000. 10.1111/sms.13016

Hegyi, A., Csala, D., Péter, A., Finni, T., & Cronin, N. J. (2019). High-density electromyography activity in various hamstring exercises. *Scandinavian Journal of Medicine & Science in Sports, 29*(1), 34–43. 10.1111/sms.13303

Henderson, G., Barnes, C. A., & Portas, M. D. (2009). Factors associated with increased propensity for hamstring injury in english premier league soccer players. *Journal of Science and Medicine in Sport, 13*(4), 397–402. 10.1016/j.jsams.2009.08.003

Hermens, H. J. (1999). *European recommendations for surface electromyography* (2. ed. ed.). Roessingh.

Hewson, D. J., Hogrel, J. -., Langeron, Y., & Duchêne, J. (2003). Evolution in impedance at the electrode-skin interface of two types of surface EMG electrodes during long-term recordings. *Journal of Electromyography and Kinesiology, 13*(3), 273–279. 10.1016/S1050-6411(02)00097-4

Hill, A. V. (1938). The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society of London. Series B, Biological Sciences, 126*(843), 136–195. 10.1098/rspb.1938.0050

Ho, J., Tumkaya, T., Aryal, S., Choi, H., & Claridge-Chang, A. (2019). Moving beyond P values: Data analysis with estimation graphics. *Nature Methods, 16*(7), 565–566. 10.1038/s41592-019-0470-3

Hori, N., Newton, R., Kawamori, N., McGuigan, M., Kraemer, W., & Nosaka, K. (2009). Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. *Journal of Strength and Conditioning Research, 23*(3), 874–882. 10.1519/JSC.0b013e3181a00ca2

Howden Broking Group Limited. (2022). 'Feeling the strain': Howden's men's european football injury index. https://www.howdengroup.com/howdens-mens-european-football-injury-index-latest-edition

Howden Broking Group Limited. (2023). Howden's 2022/23 men's european football injury index. https://www.howdengroupholdings.com/news/howden-2022-23-mens-european-football-injury-index

Iga, J., Fruer, C. S., Deighan, M., Croix, M. D. S., & James, D. V. B. (2012). 'Nordic' hamstrings exercise – engagement characteristics and training responses. *International Journal of Sports Medicine, 33*(12), 1000–1004. 10.1055/s-0032-1304591

Impellizzeri, F. M., McCall, A., & van Smeden, M. (2021). Why methods matter in a meta-analysis: A reappraisal showed inconclusive injury preventive effect of nordic hamstring exercise. *Journal of Clinical Epidemiology, 140*, 111–124. 10.1016/j.jclinepi.2021.09.007

Impellizzeri, F. M., Bizzini, M., Rampinini, E., Cereda, F., & Maffiuletti, N. A. (2008). Reliability of isokinetic strength imbalance ratios measured using the cybex NORM dynamometer. *Clinical Physiology and Functional Imaging, 28*(2), 113–119. 10.1111/j.1475-097X.2007.00786.x

Iossifidou, A. N., & Baltzopoulos, V. (1996). Angular velocity in eccentric isokinetic dynamometry. *Isokinetics and Exercise Science, 6*(1), 65–70. 10.3233/IES-1996-6111

Ishøi, L., Hölmich, P., Aagaard, P., Thorborg, K., Bandholm, T., & Serner, A. (2018). Effects of the nordic hamstring exercise on sprint capacity in male football players: A randomized controlled trial. *Journal of Sports Sciences, 36*(14), 1663–1672. 10.1080/02640414.2017.1409609

Jäppinen, A., Hämäläinen, H., Kettunen, T., & Piirainen, A. (2020). Patient education in physiotherapy in total hip arthroplasty (THA) - the perspective of physiotherapists. *Physiotherapy Theory and Practice, 36*(8), 946–955. 10.1080/09593985.2018.1513617

Jeanguyot, E., Salcinovic, B., Johnson, A., van Dyk, N., & Whiteley, R. (2023). Eccentric hamstring strength in young athletes is best documented when normalised to body mass: A cross-sectional study with normative data of 590 athletes from different age categories. *Biology of Sport, 40*(4), 1079–1095. 10.5114/biolsport.2023.125585

Jensen, C., Vasseljen, O., & Westgaard, R. H. (1993). The influence of electrode position on bipolar surface electromyogram recordings of the upper trapezius muscle. *European Journal of Applied Physiology and Occupational Physiology, 67*(3), 266. https://www.ncbi.nlm.nih.gov/pubmed/8223542

Jidovtseff, B., Quievre, J., Harris, N. K., & Cronin, J. B. (2014). Influence of jumping strategy on kinetic and kinematic variables. *Journal of Sports Medicine and Physical Fitness, 54*(2), 129–138. https://www.ncbi.nlm.nih.gov/pubmed/24509983

Schuermans, J., Danneels, L., Van Tiggelen, D., Palmans, T., & Witvrouw. E. (2017). Proximal neuromuscular control protects against hamstring injuries in male soccer players: A prospective study with electromyography time-series analysis during maximal sprinting. *The American Journal of Sports Medicine, 45*(6), 1315–1325. 10.1177/0363546516687750

Julian, R., Page, R. M., & Harper, L. D. (2021). The effect of fixture congestion on performance during professional male soccer match-play: A systematic critical review with meta-analysis. *Sports Medicine (Auckland), 51*(2), 255–273. 10.1007/s40279-020-01359-9

Kalema, R. N., Duhig, S. J., Williams, M. D., Donaldson, A., & Shield, A. J. (2022). Sprinting technique and hamstring strain injuries: A concept mapping study. *Journal of Science and Medicine in Sport, 25*(3), 209–215. 10.1016/j.jsams.2021.09.007

Kamandulis, S., Janusevicius, D., Snieckus, A., Satkunskienė, D., Skurvydas, A., & Degens, H. (2020). High-velocity elastic-band training improves hamstring muscle activation and strength in basketball players. *Journal of Sports Medicine and Physical Fitness, 60*(3), 380–387. 10.23736/S0022-4707.19.10244-7

Kassiano, W., Costa, B., Nunes, J. P., Ribeiro, A. S., Schoenfeld, B. J., & Cyrino, E. S. (2023). Which ROMs lead to rome? A systematic review of the effects of range of motion on muscle hypertrophy. *Journal of Strength and Conditioning Research, 37*(5), 1135–1144. 10.1519/JSC.0000000000004415

Kawama, R., Takahashi, K., & Wakahara, T. (2020). Effect of hip joint position on electromyographic activity of the individual hamstring muscles during stiff-leg deadlift. *Journal of Strength and Conditioning Research,* , 1. 10.1519/JSC.0000000000003442

Kazue Mizumura, & Toru Taguchi. (2016). Delayed onset muscle soreness : Involvement of neurotrophic factors. *The Journal of Physiological Sciences, 66*(1), 43–52.

Keller, M., Lauber, B., Gehring, D., Leukel, C., & Taube, W. (2014). Jump performance and augmented feedback: Immediate benefits and long-term training effects. *Human Movement Science, 36*, 177–189. 10.1016/j.humov.2014.04.007

Kellis, E., & Blazevich, A. (2023). Hamstrings force-length relationships and their implications for angle-specific joint torques: A narrative review.*12*(3), 343–358. 10.1016/j.jshs.2022.01.002

Kellis, E., & Baltzopoulos, V. (1996). The effects of normalization method on antagonistic activity patterns during eccentric and concentric isokinetic knee extension and flexion. *Journal of Electromyography and Kinesiology, 6*(4), 235–245. 10.1016/S1050-6411(96)00012-0

Kellis, E., & Sahinis, C. (2022). Is muscle architecture different in athletes with a previous hamstring strain? A systematic review and meta-analysis. *Journal of Functional Morphology and Kinesiology, 7*(1), 16. 10.3390/jfmk7010016

Kellis, E., Sahinis, C., & Baltzopoulos, V. (2023). Is hamstrings-to-quadriceps torque ratio useful for predicting anterior cruciate ligament and hamstring injuries? A systematic and critical review. *Journal of Sport and Health Science, 12*(3), 343–358. 10.1016/j.jshs.2022.01.002

Kenneally-Dabrowski, C. J. B., Brown, N. A. T., Lai, A. K. M., Perriman, D., Spratford, W., & Serpell, B. G. (2019). Late swing or early stance? A narrative review of hamstring injury mechanisms during high-speed running. *Scandinavian Journal of Medicine & Science in Sports, 29*(8), 1083–1091. 10.1111/sms.13437

Kirkendall, D. T., & Garrett, W. E. (1998). The effects of aging and training on skeletal muscle. *The American Journal of Sports Medicine, 26*(4), 598–602. 10.1177/03635465980260042401

Knudson, D. V., & Johnston, D. (1993). Comparison of EMG normalization methods in a sit-to-stand movement. *Journal of Human Movement Studies, 25*, 39–50.

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine, 15*(2), 155–163. 10.1016/j.jcm.2016.02.012

Kroulouris, G., & Connell, D. (2003). Evaluation of the hamstring muscle complex following acute injury. *Skeletal Radiology, 32*(10), 582–589. 10.1007/s00256-003-0674-5

Kraemer, W. J., Fleck, S. J., Maresh, C. M., Ratamess, N. A., Gordon, S. E., Goetz, K. L., Harman, E. A., Frykman, P. N., Volek, J. S., Mazzetti, S. A., Fry, A. C., Marchitelli, L. J., & Patton, J. F. (1999). Acute hormonal responses to a single bout of heavy resistance exercise in trained power lifters and untrained men. *Applied Physiology, Nutrition, and Metabolism, 24*(6), 524. https://www.proquest.com/docview/205836073/abstract/

Kraemer, W., Clark, M., & Schmotzer, P. (1982). Kinesiology corner: The good morning exercise. *National Strength Coaches Association Journal, 4*(1), 44. 10.1519/0199-610X(1982)004<0044:TGME>2.3.CO;2

Lauersen, J. B., Andersen, T. E., & Andersen, L. B. (2018). Strength training as superior, dose-dependent and safe prevention of acute and overuse sports injuries: A systematic review, qualitative analysis and meta-analysis. *British Journal of Sports Medicine, 52*(24), 1557–1563. 10.1136/bjsports-2018-099078

Lauersen, J. B., Bertelsen, D. M., & Andersen, L. B. (2014). The effectiveness of exercise interventions to prevent sports injuries: A systematic review and meta-analysis of randomised controlled trials. *British Journal of Sports Medicine, 48*(11), 871–877. 10.1136/bjsports-2013-092538

Lee, S., Schultz, J., Timgren, J., Staelgraeve, K., Miller, M., & Liu, Y. (2018). An electromyographic and kinetic comparison of conventional and romanian deadlifts. *Journal of Exercise Science & Fitness, 16*(3), 87–93. 10.1016/j.jesf.2018.08.001

Lees, A., Vanrenterghem, J., & Clercq, D. D. (2004). Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics, 37*(12), 1929–1940. 10.1016/j.jbiomech.2004.02.021

Lehman, G. J., & McGill, S. M. (1999). The importance of normalization in the interpretation of surface electromyography: A proof of principle. *Journal of Manipulative and Physiological Therapeutics, 22*(7), 444–446. 10.1016/S0161-4754(99)70032-1

Lieber, R. L. (1991). Frog semitendinosus tendon load-strain and stress-strain properties during passive loading. *Am J Physiol, 261*, 86.

Loturco, I., T. Freitas, T., E. Alcaraz, P., Kobal, R., Hartmann Nunes, R. F., Weldon, A., & Pereira, L. A. (2022). Practices of strength and conditioning coaches in brazilian elite soccer. *Biology of Sport,* 10.5114/biolsport.2022.108703

Lu, S., Hong, R., Chou, W., & Hsiao, P. (2015). Role of physiotherapy and patient education in lymphedema control following breast cancer surgery. *Therapeutics and Clinical Risk Management, 11*, 319–327. 10.2147/TCRM.S77669

Lynn, S. K., & Costigan, P. A. (2008). Changes in the medial–lateral hamstring activation ratio with foot rotation during lower limb exercise. *Journal of Electromyography and Kinesiology, 19*(3), e197–e205. 10.1016/j.jelekin.2008.01.007

Maganaris, C. N. (2002). Tensile properties of in vivo human tendinous tissue. *Journal of Biomechanics, 35*(8), 1019–1027. 10.1016/S0021-9290(02)00047-7

Mair, S. D., Seaber, A. V., Glisson, R. R., & Garrett, W. E. (1996). The role of fatigue in susceptibility to acute muscle strain injury. *The American Journal of Sports Medicine, 24*(2), 137–143. 10.1177/036354659602400203

Malone, S., Owen, A., Mendes, B., Hughes, B., Collins, K., & Gabbett, T. J. (2017). High-speed running and sprinting as an injury risk factor in soccer: Can well-developed physical qualities reduce the risk? *Journal of Science and Medicine in Sport, 21*(3), 257–262. 10.1016/j.jsams.2017.05.016

Maniar, N., Shield, A. J., Williams, M. D., Timmins, R. G., & Opar, D. A. (2016). Hamstring strength and flexibility after hamstring strain injury: A systematic review and meta-analysis. *British Journal of Sports Medicine, 50*(15), 909–920. 10.1136/bjsports-2015-095311

Mann, R., & Sprague, P. (1980). A kinetic analysis of the ground leg during sprint running. *Research Quarterly for Exercise and Sport, 51*(2), 334–348. 10.1080/02701367.1980.10605202

Marchiori, C. L., Medeiros, D. M., Severo-Silveira, L., dos Santos Oliveira, G., Medeiros, T. M., de Araujo Ribeiro-Alvares, J. B., & Baroni, B. M. (2022). Muscular adaptations to training programs using the nordic hamstring exercise or the stiff-leg deadlift in rugby players. *Sport Sciences for Health, 18*(2), 415–423. 10.1007/s11332-021-00820-0

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. 10.1519/1533-4287(2004)18<551:RAFVOS>2.0.CO;2

Markovic, G., Sarabon, N., Boban, F., Zoric, I., Jelcic, M., Sos, K., & Scappaticci, M. (2018). Nordic hamstring strength of highly trained youth football players and its relation to sprint performance. *Journal of Strength and Conditioning Research,* , 1. 10.1519/JSC.0000000000002800

McAllister, M., Hammond, K., Schilling, B., Ferreria, L., Reed, J., & Weiss, L. (2014). Muscle activation during various hamstring exercises. *Journal of Strength and Conditioning Research, 28*(6), 1573–1580. 10.1519/JSC.0000000000000302

McGill, S. M. (1991). Electromyographic activity of the abdominal and low back musculature during the generation of isometric and dynamic axial trunk torque: Implications for lumbar mechanics. *Journal of Orthopaedic Research : Official Publication of the Orthopaedic Research Society, 9*(1), 91–103. 10.1002/jor.1100090112

McMahon, J. J., Suchomel, T. J., Lake, J. P., & Comfort, P. (2018). Understanding the key phases of the countermovement jump force-time curve. *Strength & Conditioning Journal, 40*(4), 96–106. 10.1519/ssc.0000000000000375

Medeiros, D. M., Marchiori, C., & Baroni, B. M.Effect of nordic hamstring exercise training on knee flexors eccentric strength and fascicle length: A systematic review and meta-analysis. *Journal of Sport Rehabilitation, 30*(3), 482–491.

Mendiguchia, J., Martinez-Ruiz, E., Morin, J. B., Samozino, P., Edouard, P., Alcaraz, P. E., Esparza-Ros, F., & Mendez-Villanueva, A. (2015). Effects of hamstring-emphasized neuromuscular training on strength and sprinting mechanics in football players. *Scandinavian Journal of Medicine & Science in Sports, 25*(6), e621–e629. 10.1111/sms.12388

Mendiguchia, J., Alentorn-Geli, E., & Brughelli, M. (2012). Hamstring strain injuries: Are we heading in the right direction? *British Journal of Sports Medicine, 46*(2), 81–85. 10.1136/bjsm.2010.081695

Mendiguchia, J., Conceição, F., Edouard, P., Fonseca, M., Pereira, R., Lopes, H., Morin, J., & Jiménez-Reyes, P. (2020). Sprint versus isolated eccentric training: Comparative effects on hamstring architecture and performance in soccer players. *PLoS ONE, 15*(2), e0228283. 10.1371/journal.pone.0228283

Merrigan, J. J., Strang, A., Eckerle, J., Mackowski, N., Hierholzer, K., Ray, N. T., Smith, R., Hagen, J. A., & Briggs, R. A. (2024). Countermovement jump force-time curve analyses: Reliability and comparability across force plate systems. *Journal of Strength and Conditioning Research, 38*(1), 30–37. 10.1519/JSC.0000000000004586

Mjolsnes, R., Arnason, A., osthagen, T., Raastad, T., & Bahr, R. (2004). A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scandinavian Journal of Medicine & Science in Sports, 14*(5), 311–317. 10.1046/j.1600-0838.2003.367.x

Morgan, D. L., Brockett, C. L., Gregory, J. E., & Proske, U. (2002). The role of the length-tension curve in the control of movement. *Advances in experimental medicine and biology* (pp. 489–494). Springer US. 10.1007/978-1-4615-0713-0_55

Morgan, D. L. (1990). New insights into the behavior of muscle during active lengthening. *Biophysical Journal, 57*(2), 209–221. 10.1016/S0006-3495(90)82524-8

Morgan, D. L., & Proske, U. (2004). Popping sarcomere hypothesis explains stretch-induced muscle damage. *Clinical and Experimental Pharmacology and Physiology, 31*(8), 541–545. 10.1111/j.1440-1681.2004.04029.x

Morgans, R., Bezuglov, E., Orme, P., Burns, K., Rhodes, D., Babraj, J., Di Michele, R., & Oliveira, R. F. S. (2022). The physical demands of match-play in academy and senior soccer players from the scottish premiership. *Sports (Basel), 10*(10), 150. 10.3390/sports10100150

Morin, J. B., Edouard, P., & Samozino, P. (2011). Technical ability of force application as a determinant factor of sprint performance. *Medicine & Science in Sports & Exercise, 43*(9), 1680–1688. 10.1249/mss.0b013e318216ea37

Morin, J., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J. (2012). Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology, 112*(11), 3921–3930. 10.1007/s00421-012-2379-8

Morin, J., Gimenez, P., Edouard, P., Arnal, P., Jiménez-Reyes, P., Samozino, P., Brughelli, M., & Mendiguchia, J. (2015). Sprint acceleration mechanics: The major role of hamstrings in horizontal force production. *Frontiers in Physiology, 6*, 404–404. 10.3389/fphys.2015.00404

Morin, J., Jiménez-Reyes, P., Brughelli, M., & Samozino, P. (2019). When jump height is not a good indicator of lower limb maximal power output: Theoretical demonstration, experimental evidence and practical solutions. *Sports Medicine (Auckland), 49*(7), 999–1006. 10.1007/s40279-019-01073-1

Morris, A. D., Kemp, G. J., Lees, A., & Frostick, S. P. (1998). A study of the reproducibility of three different normalisation methods in intramuscular dual fine wire electromyography of the shoulder. *Journal of Electromyography and Kinesiology, 8*(5), 317–322. 10.1016/S1050-6411(98)00002-9

Mudge, S., Stretton, C., & Kayes, N. (2014). Are physiotherapists comfortable with person-centred practice? an autoethnographic insight. *Disability and Rehabilitation, 36*(6), 457–463. 10.3109/09638288.2013.797515

Nagano, Y., Higashihara, A., Takahashi, K., & Fukubayashi, T. (2014). Mechanics of the muscles crossing the hip joint during sprint running. *Journal of Sports Sciences, 32*(18), 1722–1728. 10.1080/02640414.2014.915423

Narouei, S., Imai, A., Akuzawa, H., Hasebe, K., & Kaneoka, K. (2018). Hip and trunk muscles activity during nordic hamstring exercise. *Journal of Exercise Rehabilitation, 14*(2), 231–238. 10.12965//jer.1835200.600

Nejc Šarabon, Jan Marušič, Goran Marković, & Žiga Kozinc. (2019). Kinematic and electromyographic analysis of variations in nordic hamstring exercise. *Plos One, 14*(10), e0–e0223437. 10.1371/journal.pone.0223437

Nishijima, Y., Kato, T., Yoshizawa, M., Miyashita, M., & Iida, H. (2010). Application of the segment weight dynamic movement method to the normalization of gait EMG amplitude. *Journal of Electromyography and Kinesiology, 20*(3), 550–557. 10.1016/j.jelekin.2009.07.006

Ono, T., Higashihara, A., & Fukubayashi, T. (2010). Hamstring functions during hip-extension exercise assessed with electromyography and magnetic resonance imaging. *Research in Sports Medicine, 19*(1), 42–52. 10.1080/15438627.2011.535769

Opar, D. A., Williams, M. D., & Shield, A. J. (2012). Hamstring strain injuries. *Sports Medicine (Auckland), 42*(3), 209–226. 10.2165/11594800-000000000-00000

Opar, D. A., Piatkowski, T., Williams, M. D., & Shield, A. J. (2013). A novel device using the nordic hamstring exercise to assess eccentric knee flexor strength: A reliability and retrospective injury study. *The Journal of Orthopaedic and Sports Physical Therapy, 43*(9), 636–640. 10.2519/jospt.2013.4837

Opar, D., Williams, M., Timmins, R., Hickey, J., Duhig, S., & Shield, A. (2015). Eccentric hamstring strength and hamstring injury risk in australian footballers. *Medicine & Science in Sports & Exercise, 47*(4), 857–865. 10.1249/MSS.0000000000000465

Orchard, J., & Seward, H. (2002). Epidemiology of injuries in the australian football league, seasons 1997-2000. *British Journal of Sports Medicine, 36*(1), 39–44. 10.1136/bjsm.36.1.39

Orchard, J. W., Kountouris, A., & Sims, K. (2017). Risk factors for hamstring injuries in australian male professional cricket players. *Journal of Sport and Health Science, 6*(3), 271–274. 10.1016/j.jshs.2017.05.004

Orchard, J., & Best, T. (2002). The management of muscle strain injuries: An early return versus the risk of recurrence. *Clinical Journal of Sport Medicine, 12*(1), 3–5. 10.1097/00042752-200201000-00004

Orchard, J., & Seward, H. (2010, Injury report 2009: Australian football league. *Sport Health, 28*, 10-

19. http://search.informit.com.au/documentSummary;dn=457421793031572;res=IELHEA

Orchard, J., Wood, T., Seward, H., & Broad, A. (1998). Comparison of injuries in elite senior and junior australian football. *Journal of Science and Medicine in Sport, 1*(2), 83–88. 10.1016/S1440-2440(98)80016-9

Panayi, S. (2010). The need for lumbar–pelvic assessment in the resolution of chronic hamstring strain. *Journal of Bodywork and Movement Therapies, 14*(3), 294–298. 10.1016/j.jbmt.2009.08.004

Pappas, G. P., Asakawa, D. S., Delp, S. L., Zajac, F. E., & Drace, J. E. (2002). Nonuniform shortening in the biceps brachii during elbow flexion. *Journal of Applied Physiology, 92*(6), 2381–2389. 10.1152/japplphysiol.00843.2001

Petersen, J., Thorborg, K., Nielsen, M. B., Budtz-Jørgensen, E., & Hölmich, P. (2011). Preventive effect of eccentric training on acute hamstring injuries in men's soccer. *The American Journal of Sports Medicine, 39*(11), 2296–2303. 10.1177/0363546511419277

Pick, J., & Becque, M. D. (2000). The relationship between training status and intensity on muscle activation and relative submaximal lifting capacity during the back squat. *Journal of Strength and Conditioning Research, 14*(2), 175–181. 10.1519/00124278-200005000-00010

Pincheira, P. A., Boswell, M. A., Franchi, M. V., Delp, S. L., & Lichtwark, G. A. (2022). Biceps femoris long head sarcomere and fascicle length adaptations after 3 weeks of eccentric exercise training. *Journal of Sport and Health Science, 11*(1), 43–49. 10.1016/j.jshs.2021.09.002

Presland, J. D., Timmins, R. G., Bourne, M. N., Williams, M. D., & Opar, D. A. (2018). The effect of Nordic hamstring exercise training volume on biceps femoris long head architectural adaptation. *Scandinavian Journal of Medicine & Science in Sports, 28*(7), 1775–1783. 10.1111/sms.13085

Presland, J., Timmins, R., Bourne, M., Williams, M., & Opar, D. (2017). The effect of high or low volume Nordic hamstring exercise training on eccentric strength and biceps femoris long head architectural adaptations. *Journal of Science and Medicine in Sport, 20*, 12. 10.1016/j.jsams.2017.09.213

Rabita, G., Dorel, S., Slawinski, J., Sàez-de-Villarreal, E., Couturier, A., Samozino, P., & Morin, J. (2015). Sprint mechanics in world-class athletes: A new insight into the limits of human locomotion. *Scandinavian Journal of Medicine & Science in Sports, 25*(5), 583–594. 10.1111/sms.12389

Ramírez-delaCruz, M., Bravo-Sánchez, A., Esteban-García, P., Jiménez, F., & Abián-Vicén, J. (2022a). Effects of plyometric training on lower body muscle architecture, tendon structure, stiffness and physical performance: A systematic review and meta-analysis. *Sports Medicine - Open, 8*(1), 40. 10.1186/s40798-022-00431-0

Ramírez-delaCruz, M., Bravo-Sánchez, A., Esteban-García, P., Jiménez, F., & Abián-Vicén, J. (2022b). Effects of plyometric training on lower body muscle architecture, tendon structure, stiffness and physical performance: A systematic review and meta-analysis. *Sports Medicine - Open, 8*(1), 40. 10.1186/s40798-022-00431-0

Randell, A., Cronin, J., Keogh, J., Gill, N., & Pedersen, M. (2011). Effect of instantaneous performance feedback during 6 weeks of velocity-based resistance training on sport-specific performance tests. *Journal of Strength and Conditioning Research, 25*(1), 87–93. 10.1519/JSC.0b013e3181fee634

Reeves, N. D., Maganaris, C. N., Longo, S., & Narici, M. V. (2009). Differential adaptations to eccentric versus conventional resistance training in older humans. *Experimental Physiology, 94*(7), 825–833. 10.1113/expphysiol.2009.046599

Reeves, N. D., Maganaris, C. N., & Narici, M. V. (2005). Plasticity of dynamic muscle performance with strength training in elderly humans. *Muscle & Nerve, 31*(3), 355–364. 10.1002/mus.20275

Rehorn, M. R. |., Silvia S. (2010). The effects of aponeurosis geometry on strain injury susceptibility explored with a 3D muscle model. *Journal of Biomechanics, 43*(13), 2574–2581. 10.1016/j.jbiomech.2010.05.011

Rey, E., Paz-Domínguez, Á, Porcel-Almendral, D., Paredes-Hernández, V., Barcala-Furelos, R., & Abelairas-Gómez, C. (2017). Effects of a 10-week nordic hamstring exercise and russian belt training on posterior lower-limb muscle strength in elite junior soccer players. *Journal of Strength and Conditioning Research, 31*(5), 1198–1205. 10.1519/JSC.0000000000001579

Reynolds, J., Connor, M., Jamil, M., & Beato, M. (2021). Quantifying and comparing the match demands of U18, U23, and 1ST team english professional soccer players. *Frontiers in Physiology, 12*, 706451. 10.3389/fphys.2021.706451

Ribeiro-Alvares, J., Marques, V., Vaz, M., & Baroni, B. (2018). Four weeks of nordic hamstring exercise reduce muscle injury risk factors in young adults. *Journal of*

Strength and Conditioning Research, 32(5), 1254–1262. 10.1519/JSC.0000000000001975

Richens, B., & Cleather, D. J. (2014). The relationship between the number of repetitions performed at given intensities is different in endurance and strength trained athletes. http://research.stmarys.ac.uk/886/

Ripley, N. J., Cuthbert, M., Comfort, P., & McMahon, J. J. (2023). Effect of additional nordic hamstring exercise or sprint training on the modifiable risk factors of hamstring strain injuries and performance. *PloS One, 18*(3), e0281966. 10.1371/journal.pone.0281966

Ripley, N. J., Cuthbert, M., Ross, S., Comfort, P., & McMahon, J. J. (2021). The effect of exercise compliance on risk reduction for hamstring strain injury: A systematic review and meta-analyses. *International Journal of Environmental Research and Public Health, 18*(21), 11260. 10.3390/ijerph182111260

Robinson, M. A., Vanrenterghem, J., & Pataky, T. C. (2021). Sample size estimation for biomechanical waveforms: Current practice, recommendations and a comparison to discrete power analysis. *Journal of Biomechanics, 122*, 110451. doi: 10.1016/j.jbiomech.2021.110451

Roe, M., Murphy, J. C., Gissane, C., & Blake, C. (2018). Hamstring injuries in elite gaelic football: An 8-year investigation to identify injury rates, time-loss patterns and players at increased risk. *British Journal of Sports Medicine, 52*(15), 982–988. 10.1136/bjsports-2016-096401

Rohatgi A. (2015). WebPlotDigitizer (Version 3.9) [Computer software]. Retrieved from http://arohatgi.info/WebPlotDigitizer

Ross, S., Comfort, P., Ripley, N. J., & Cuthbert, M. (Jul 10, 2019). Within-session reliability of three methods of electromyography normalization for hamstring and gluteal muscles. Paper presented at the *National Strength and Conditioning Association National Conference,* https://research.edgehill.ac.uk/en/publications/eb723d73-2454-4f91-8eda-800cfcd43297

Ross, S., Comfort, P., Jones, P., A, Ripley, N., J, Owen, C., & McMahon, J., J. (2020). Reliability and comparison of force characteristics of the nodic hamstring exercise. *38th International Society of Biomechanics in Sport Conference,* https://commons.nmu.edu/cgi/viewcontent.cgi?article=2092&context=isbs

Ross, S., Comfort, P., & McMahon, J. (2024). The good Morning—Exercise technique and exercise selection principles. *Strength and Conditioning Journal, 46*(3), 378–382. 10.1519/SSC.0000000000000802

Rouffet, D. M., & Hautier, C. A. (2008). EMG normalization to study muscle activation in cycling. *Journal of Electromyography and Kinesiology, 18*(5), 866–878. 10.1016/j.jelekin.2007.03.008

Rudisill, S. S., Varady, N. H., Kucharik, M. P., Eberlin, C. T., & Martin, S. D. (2023). Evidence-based hamstring injury prevention and risk factor management: A systematic review and meta-analysis of randomized controlled trials. *The American Journal of Sports Medicine, 51*(7), 1927–1942. 10.1177/03635465221083998

Ryan, L. M., Magidow, P. S., & Duncan, P. W. (1991). Velocity-specific and mode-specific effects of eccentric isokinetic training of the hamstrings. *Journal of*

Orthopaedic & Sports Physical Therapy, 13(1), 33–39. 10.2519/jospt.1991.13.1.33

Salci, Y., Yildirim, A., Celik, O., Ak, E., Kocak, S., & Korkusuz, F. (2013). The effects of eccentric hamstring training on lower extremity strength and landing kinetics in recreational female athletes. *Isokinetics and Exercise Science, 21*(1), 11–18. 10.3233/IES-2012-0466

Sallay, P. I., Friedman, R. L., Coogan, P. G., & Garrett, W. E. (1996). Hamstring muscle injuries among water skiers. *The American Journal of Sports Medicine, 24*(2), 130–136. 10.1177/036354659602400202

Sancese, A., Taylor, L., Walsh, G., Byrd, E., & Delextrat, A. (2023). Effects of sprint versus strength training on risk factors for hamstring injury in football players. *Journal of Sports Medicine and Physical Fitness, 63*(4), 580–587. 10.23736/S0022-4707.22.14529-9

Sanfilippo, J. L., Silder, A., Sherry, M. A., Tuite, M. J., & Heiderscheit, B. C. (2013). Hamstring strength and morphology progression after return to sport from injury. *Medicine and Science in Sports and Exercise, 45*(3), 448–454. 10.1249/MSS.0b013e3182776eff

Saw, R., Finch, C. F., Samra, D., Baquie, P., Cardoso, T., Hope, D., & Orchard, J. W. (2018). Injuries in australian rules football: An overview of injury rates, patterns, and mechanisms across all levels of play. *Sports Health: A Multidisciplinary Approach, 10*(3), 208–216. 10.1177/1941738117726070

Schache, A. G., Dorn, T. W., Blanch, P. D., Brown, N. A. T., & Pandy, M. G. (2012). Mechanics of the human hamstring muscles during sprinting. *Medicine and*

Science in Sports and Exercise, 44(4), 647–658. 10.1249/mss.0b013e318236a3d2

Schoenfeld, B., Contreras, B., Tiryaki-Sonmez, G., Wilson, J., Kolber, M., & Peterson, M. (2015). Regional differences in muscle activation during hamstrings exercise. *Journal of Strength and Conditioning Research, 29*(1), 159–164. 10.1519/JSC.0000000000000598

Selseth, A., Dayton, M., Cordova, M. L., Ingersoll, C. D., & Merrick, M. A. (2000). Quadriceps concentric EMG activity is greater than eccentric EMG activity during the lateral step-up exercise. *Journal of Sport Rehabilitation, 9*(2), 124–134. 10.1123/jsr.9.2.124

Severo-Silveira, L., Dornelles, M., Lima-e-Silva, F., Marchiori, C., Medeiros, T., Pappas, E., & Baroni, B. (2018). Progressive workload periodization maximizes effects of nordic hamstring exercise on muscle injury risk factors. *Journal of Strength and Conditioning Research,* , 1. 10.1519/JSC.0000000000002849

Seward, H., Orchard, J., Hazard, H., & Collinson, D. (1993). Football injuries in australia at the élite level. *The Medical Journal of Australia, 159*(5), 298. https://www.ncbi.nlm.nih.gov/pubmed/8361423

Seymore, K. D., Domire, Z. J., DeVita, P., Rider, P. M., & Kulas, A. S. (2017). The effect of nordic hamstring strength training on muscle architecture, stiffness, and strength. *European Journal of Applied Physiology, 117*(5), 943–953. 10.1007/s00421-017-3583-3

Shahab, S., Steendahl, I. B., Ruf, L., Meyer, T., & Van Hooren, B. (2021). Sprint performance and force-velocity profiling does not differ between artificial turf and concrete. *International Journal of Sports Science & Coaching, 16*(4), 968–975. 10.1177/1747954121996966

Sherry, M. A., & Best, T. M. (2004a). A comparison of 2 rehabilitation programs in the treatment of acute hamstring strains. *Journal of Orthopaedic & Sports Physical Therapy, 34*(3), 116–125. 10.2519/jospt.2004.34.3.116

Sherry, M. A., & Best, T. M. (2004b). A comparison of 2 rehabilitation programs in the treatment of acute hamstring strains. *The Journal of Orthopaedic and Sports Physical Therapy, 34*(3), 116. 10.2519/jospt.2004.1062

Shiavi, R., Bugle, H. J., & Limbird, T. (1987). Electromyographic gait assessment, part 1: Adult EMG profiles and walking speed. *Journal of Rehabilitation Research and Development, 24*(2), 13. https://www.ncbi.nlm.nih.gov/pubmed/3585781

Shiavi, R., Bourne, J., & Holland, A. (1986). Automated extraction of activity features in linear envelopes of locomotor electromyographic patterns. *IEEE Transactions on Biomedical Engineering, BME-33*(6), 594–600. 10.1109/TBME.1986.325841

Shorter, K. A., Polk, J. D., Rosengren, K. S., & Hsiao-Wecksler, E. T. (2007). A new approach to detecting asymmetries in gait. *Clinical Biomechanics, 23*(4), 459–467. 10.1016/j.clinbiomech.2007.11.009

Siddle, J., Greig, M., Weaver, K., Page, R. M., Harper, D., & Brogden, C. M. (2019). Acute adaptations and subsequent preservation of strength and speed measures following a nordic hamstring curl intervention: A randomised controlled trial. *Journal of Sports Sciences, 37*(8), 911–920. 10.1080/02640414.2018.1535786

Silder, A. (2008). MR observations of long-term musculotendon remodeling following a hamstring strain injury. *Skeletal Radiology, 37*, 1101–1109.

Slavotinek, J. P., Verrall, G. M., & Fon, G. T. (2002). Hamstring injury in athletes: Using MR imaging measurements to compare extent of muscle injury with amount of time lost from competition. *American Journal of Roentgenology (1976), 179*(6), 1621–1628. 10.2214/ajr.179.6.1791621

Śliwowski, R., Grygorowicz, M., Hojszyk, R., & Jadczak, Ł. (2017). The isokinetic strength profile of elite soccer players according to playing position. *PloS One, 12*(7), e0182177. 10.1371/journal.pone.0182177

Small, K., McNaughton, L. R., Greig, M., Lohkamp, M., & Lovell, R. (2009). Soccer fatigue, sprinting and hamstring injury risk. *International Journal of Sports Medicine, 30*(8), 573–578. 10.1055/s-0029-1202822

Sousa, A. S. P., & Tavares, J. M. R. S. (2012). *Surface electromyographic amplitude normalization methods: A review*

Suarez-Arrones, L., Lara-Lopez, P., Rodriguez-Sanchez, P., Lazaro-Ramirez, J. L., Di Salvo, V., Guitart, M., Fuentes-Nieto, C., Rodas, G., & Mendez-Villanueva, A. (2019). Dissociation between changes in sprinting performance and nordic hamstring strength in professional male football players. *PloS One, 14*(3), e0213375. 10.1371/journal.pone.0213375

Suchomel, T. J., Comfort, P., & Lake, J. P. (2017). Enhancing the force-velocity profile of athletes using weightlifting derivatives. *Strength and Conditioning Journal, 39*(1), 10–20. 10.1519/SSC.0000000000000275

Suchomel, T. J., Comfort, P., & Stone, M. H. (2015). Weightlifting pulling derivatives: Rationale for implementation and application. *Sports Medicine (Auckland), 45*(6), 823–839. 10.1007/s40279-015-0314-y

Suchomel, T. J., Nimphius, S., Bellon, C. R., & Stone, M. H. (2018). The importance of muscular strength: Training considerations. *Sports Medicine, 48*(4), 765–785. 10.1007/s40279-018-0862-z

Sugiura, Y., Saito, T., Sakuraba, K., Sakuma, K., & Suzuki, E. (2008). Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injury in elite sprinters. *The Journal of Orthopaedic and Sports Physical Therapy, 38*(8), 457–464. 10.2519/jospt.2008.2575

Tansel, R. B., Saici, Y., Yildirim, A., Kocak, S., & Korkusuz, F. (2008). Effects of eccentric hamstring strength training on lower extremity strength of 10–12 year old male basketball players. *Isokinetics and Exercise Science, 16*(2), 81–85. 10.3233/IES-2008-0300

Thelen, D. G., Chumanov, E. S., Hoerth, D. M., Best, T. M., Swanson, S. C., Li, L. I., Young, M., & Heiderscheit, B. C. (2005). Hamstring muscle kinematics during treadmill sprinting. *Medicine & Science in Sports & Exercise, 37*(1), 108–114. 10.1249/01.mss.0000150078.79120.c8

Thomas, J. R., Nelson, J. K., & Silverman, S. J. (2011). *Research methods in physical activity* (6. ed. ed.). Human Kinetics.

Timmins, R., Bourne, M., Shield, A., Williams, M., & Opar, D. (2015). Strength and architectural risk factors for hamstring strain injury in elite australian soccer: A prospective cohort study. *Journal of Science and Medicine in Sport, 19*, e20. 10.1016/j.jsams.2015.12.425

Timmins, R. G., Bourne, M. N., Shield, A. J., Williams, M. D., Lorenzen, C., & Opar, D. A. (2016a). Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): A prospective cohort study. *British Journal of Sports Medicine, 50*(24), 1524–1535. 10.1136/bjsports-2015-095362

Timmins, R. G., Ruddy, J. D., Presland, J., Maniar, N., Shield, A. J., Williams, M. D., & Opar, D. A. (2016). Architectural changes of the biceps femoris long head after concentric or eccentric training. *Medicine & Science in Sports & Exercise, 48*(3), 499–508. 10.1249/MSS.0000000000000795

Timmins, R. G., Shield, A. J., Williams, M. D., Lorenzen, C., & Opar, D. A. (2016b). Architectural adaptations of muscle to training and injury: A narrative review outlining the contributions by fascicle length, pennation angle and muscle thickness. *British Journal of Sports Medicine, 50*(23), 1467–1472. 10.1136/bjsports-2015-094881

Tosovic, D., Muirhead, J. C., Brown, J. M. M., & Woodley, S. J. (2016). Anatomy of the long head of biceps femoris: An ultrasound study. *Clinical Anatomy (New York, N.Y.), 29*(6), 738–745. 10.1002/ca.22718

Tsaklis, P., Malliaropoulos, N., Mendiguchia, J., Korakakis, V., Tsapralis, K., Pyne, D., & Malliaras, P. (2015). Muscle and intensity based hamstring exercise classification in elite female track and field athletes: Implications for exercise selection during rehabilitation. *Open Access Journal of Sports Medicine, 6*, 209–217. 10.2147/oajsm.s79189 van den Tillaar, R., Solheim, J. A. B., & Bencke, J. (2017). Comparison of hamstring muscle activation during high-speed running and various hamstring strengthening exercises. *International Journal of Sports Physical Therapy, 12*(5), 718–727. 10.26603/ijspt20170718

van der Horst, N., Smits, D., Petersen, J., Goedhart, E. A., & Backx, F. J. G. (2015). The preventive effect of the nordic hamstring exercise on hamstring injuries in amateur soccer players : A randomized controlled trial. *The American Journal of Sports Medicine, 43*(6), 1316–1323. 10.1177/0363546515574057

van Dyk, N., Witvrouw, E., & Bahr, R. (2018). Interseason variability in isokinetic strength and poor correlation with nordic hamstring eccentric strength in football players. *Scandinavian Journal of Medicine & Science in Sports, 28*(8), 1878–1887. 10.1111/sms.13201

van Dyk, N., Bahr, R., Whiteley, R., Tol, J. L., Kumar, B. D., Hamilton, B., Farooq, A., & Witvrouw, E. (2016). Hamstring and quadriceps isokinetic strength deficits are weak risk factors for hamstring strain injuries: A 4-year cohort study. *American Journal of Sports Medicine, 44*(7), 1789–1795. 10.1177/0363546516632526

van Dyk, N., Behan, F. P., & Whiteley, R. (2019). Including the nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: A systematic review and meta-analysis of 8459 athletes. *British Journal of Sports Medicine, 53*(21), 1362–1370. 10.1136/bjsports-2018-100045

Van Hooren, B., & Bosch, F. (2017a). Is there really an eccentric action of the hamstrings during the swing phase of high-speed running? part I: A critical review of the literature. *Journal of Sports Sciences, 35*(23), 2313–2321. 10.1080/02640414.2016.1266018

Van Hooren, B., & Bosch, F. (2017b). Is there really an eccentric action of the hamstrings during the swing phase of high-speed running? part II: Implications for exercise. *Journal of Sports Sciences, 35*(23), 2322–2333. 10.1080/02640414.2016.1266019

Van Hooren, B., Vanwanseele, B., Rossom, S., Teratsias, P., Willems, P., Drost, M., & Meijer, K. (2022). Muscle forces and fascicle behavior during three hamstring exercises. *Scandinavian Journal of Medicine & Science in Sports, 32*(6), 997–1012. 10.1111/sms.14158

Verrall, G. M., Slavotinek, J. P., Barnes, P. G., & Fon, G. T. (2003). Diagnostic and prognostic value of clinical findings in 83 athletes with posterior thigh injury. *The American Journal of Sports Medicine, 31*(6), 969–973. 10.1177/03635465030310063701

Vickers, A. J., & Altman, D. G. (2001). Statistics notes: Analysing controlled trials with baseline and follow up measurements. *Bmj, 323*(7321), 1123–1124. 10.1136/bmj.323.7321.1123

Vigotsky, A. D., Harper, E. N., Ryan, D. R., & Contreras, B. (2015). Effects of load on good morning kinematics and EMG activity. *PeerJ, 3*, e708. 10.7717/peerj.708

Waldron, M., Worsfold, P., Twist, C., & Lamb, K. (2011). Concurrent validity and test-retest reliability of a global positioning system (GPS) and timing gates to assess sprint performance variables. *Journal of Sports Sciences, 29*(15), 1613–1619. 10.1080/02640414.2011.608703

Wan, X., Qu, F., Garrett, W. E., Liu, H., & Yu, B. (2017). Relationships among hamstring muscle optimal length and hamstring flexibility and strength. *Journal of Sport and Health Science, 6*(3), 275–282. 10.1016/j.jshs.2016.04.009

Weir, J. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the sem. *Journal of Strength and Conditioning Research, 19*(1), 231–240. 10.1519/15184.1

Weldon, A., Duncan, M. J., Turner, A. N., Sampaio, J., Wong, D., Noon, M., & Lai, V. (2020). Contemporary practices of strength and conditioning coaches in professional soccer. http://eprints.mdx.ac.uk/30987

Weldon, A., Duncan, M. J., Turner, A., Sampaio, J., Noon, M., Wong, D., & Lai, V. W. (2021a). Contemporary practices of strength and conditioning coaches in professional soccer. *Biology of Sport, 38*(3), 377–390. 10.5114/biolsport.2021.99328

Weldon, A., Duncan, M. J., Turner, A., Christie, C. J., & Pang, C. M. (2021b). Contemporary practices of strength and conditioning coaches in professional cricket. *International Journal of Sports Science & Coaching, 16*(3), 585–600. 10.1177/1747954120977472

Weldon, A., Mak, J. T. S., Wong, S. T., Duncan, M. J., Clarke, N. D., & Bishop, C. (2021c). Strength and conditioning practices and perspectives of volleyball coaches and players. *Sports (Basel), 9*(2), 28. 10.3390/sports9020028

Weldon, A., Wong, S. T., Mateus, N., Duncan, M. J., Clarke, N. D., Pears, M., Owen, A. L., & Bishop, C. (2022). The strength and conditioning practices and perspectives of soccer coaches and players. *International Journal of Sports Science & Coaching, 17*(4), 742–760. 10.1177/17479541211072242

Weston, M. (2018). Training load monitoring in elite english soccer: A comparison of practices and perceptions between coaches and practitioners. *Science and Medicine in Football, 2*(3), 216–224. 10.1080/24733938.2018.1427883

Whyte, E., Heneghan, B., Feely, K., Moran, K., & O'Connor, S. (2019). The effect of hip extension and nordic hamstring exercise protocols on hamstring strength: A randomized controlled trial. *Journal of Strength and Conditioning Research,* , 1. 10.1519/JSC.0000000000003220

Wiesinger, H., Gressenbauer, C., Kösters, A., Scharinger, M., & Müller, E. (2020). Device and method matter: A critical evaluation of eccentric hamstring muscle strength assessments. *Scandinavian Journal of Medicine & Science in Sports, 30*(2), 217–226. 10.1111/sms.13569

Williams, M. J., Gibson, N. V., Sorbie, G. G., Ugbolue, U. C., Brouner, J., & Easton, C. (2018). Activation of the gluteus maximus during performance of the back squat, split squat, and barbell hip thrust and the relationship with maximal sprinting. *Journal of Strength and Conditioning Research,* , 1. 10.1519/JSC.0000000000002651

Wing, C., & Bishop, C. (2020). Hamstring strain injuries. *Strength and Conditioning Journal, 42*(3), 40–57. 10.1519/SSC.0000000000000538

Winkel, J., & Jørgensen, K. (1991). Significance of skin temperature changes in surface electromyography. *European Journal of Applied Physiology and Occupational Physiology, 63*(5), 345–348. 10.1007/BF00364460

Wolf, M., Androulakis-Korakakis, P., Fisher, J., Schoenfeld, B., & Steele, J. (2023). Partial vs full range of motion resistance training: A systematic review and meta-analysis. *International Journal of Strength and Conditioning, 3*(1)10.47206/ijsc.v3i1.182

Wood, G. A. (1988). Biomechanical limitations to sprint running. *Current research in sports biomechanics* (pp. 58–71). S. Karger AG. 10.1159/000414398

Woods, C., Hawkins, R. D., Maltby, S., Hulse, M., Thomas, A., & Hodson, A. (2004). The football association medical research programme: An audit of injuries in professional football--analysis of hamstring injuries. *British Journal of Sports Medicine, 38*(1), 36–41. 10.1136/bjsm.2002.002352

Worth, D. R. (1969). The hamstring injury in australian rules football. *Australian Journal of Physiotherapy, 15*(3), 111–113. 10.1016/S0004-9514(14)61080-1

Wright, G. A., Delong, T. H., & Gehlsen, G. (1999). Electromyographic activity of the hamstrings during performance of the leg curl, stiff-leg deadlift, and back squat movements. *Journal of Strength and Conditioning Research, 13*(2), 168–174. 10.1519/00124278-199905000-00012

Xu, J., Turner, A., Comyns, T. M., Chavda, S., & Bishop, C. (2024). The countermovement rebound jump: Between-session reliability and a comparison with the countermovement and drop jump tests. *Journal of Strength and Conditioning Research, 38*(4), e150–e159. 10.1519/JSC.0000000000004687

Yanagisawa, O., & Fukutani, A. (2020). Muscle recruitment pattern of the hamstring muscles in hip extension and knee flexion exercises. *Journal of Human Kinetics, 72*(1), 51–59. 10.2478/hukin-2019-0124

Yu, B., Queen, R. M., Abbey, A. N., Liu, Y., Moorman, C. T., & Garrett, W. E. (2008). Hamstring muscle kinematics and activation during overground sprinting. *Journal of Biomechanics, 41*(15), 3121–3126. 10.1016/j.jbiomech.2008.09.005

Zandbergen, M. A., Marotta, L., Bulthuis, R., Buurke, J. H., Veltink, P. H., & Reenalda, J. (2023). Effects of level running-induced fatigue on running kinematics: A systematic review and meta-analysis. *Gait & Posture, 99*, 60–75. 10.1016/j.gaitpost.2022.09.089

Zebis, M. K., Skotte, J., Andersen, C. H., Mortensen, P., Petersen, H. H., Viskaer, T. C., Jensen, T. L., Bencke, J., & Andersen, L. L. (2013). Kettlebell swing targets semitendinosus and supine leg curl targets biceps femoris: An EMG study with rehabilitation implications. *British Journal of Sports Medicine, 47*(18), 1192–1198. 10.1136/bjsports-2011-090281

Zvijac, J. E., Toriscelli, T. A., Merrick, S., & Kiebzak, G. M. (2013). Isokinetic concentric quadriceps and hamstring strength variables from the NFL scouting combine are not predictive of hamstring injury in first-year professional football players. *The American Journal of Sports Medicine, 41*(7), 1511–1518. 10.1177/0363546513487983

Appendices

Appendix 1.0 Practitioner Survey

Link to full practitioner survey

Appendix 2.0 Practitioner Survey Participant Information Sheet

Dear practitioner,

You are invited to consider volunteering as a participant for an upcoming questionnaire-based study entitled '*Practices and perceptions of hamstring training across sports, practitioners and geographical regions.'* The study is planned to take place online and will be completely anonymous.

In recent years, there has been a surge in the volume of published literature in the field of hamstring strain injury, however despite this there has been little evidence of a decrease in injury occurrence in sport. Additionally, the sports that are associated with high hamstring strain injury rates have a broad range of unique sporting demands and training needs.

The study aims to investigate the applied practices of hamstring focussed training in sport, with a particular focus on implementation of high-speed running and resistance training as a means of reducing the incidence and/or risk of hamstring strain injury or the use of training for enhanced athletic performance.

The questionnaire will comprise of a series of questions about your professional profile (such as gender, age, qualifications and job role); off-season and in-season practices relating to hamstring resistance training and/or use of high-speed running; general approaches to implementation of training and athlete testing and finally, a series of open-ended questions to explore the perceptions of the practitioner, limitations/challenges in applied practice and your overall thoughts on what aspects of training you perceive to be key in training of the hamstring region.

Taking part in this study will require you to complete one online questionnaire, which will be completely anonymous, meaning that your identity or the identify of your organisation will not be disclosed to the investigators. It is anticipated that the questionnaire will take approximately 15 - 20 minutes to complete. You have the right to withdraw from the study at any point during the questionnaire, by simply exiting and not submitting your answers. In that scenario, none of your answers will be submitted to the investigator. Unfortunately, if you wish to withdraw from the study after submitting your answers, you can do so but you would be required to divulge your identity to the primary researcher, so that they can ensure that the correct set of question responses are removed from the study. Should you wish to withdraw after submitting your responses, then you can do so for a period of up to 3-weeks following submission of your responses without being disadvantaged in any way and your responses will be permanently deleted.

Upon completion of the questionnaire, you will be asked whether you would be willing to take part in a future interview / focus group with the principal investigator, however this is completely optional.

The results of this study will be presented as part of the principal investigator's doctoral thesis at the University of Salford, United Kingdom, and may be presented as part of a peer-reviewed journal submission or conference presentation, however no participant information will be shared at any point.

If you feel that you would be interested in participating in this study, then please visit the link below to view the informed consent information and complete the questionnaire. You are advised to take at least 24 hours from reviewing this invitation to consider whether you would like to take part.

Questionnaire link: https://forms.gle/KNUuh3JoGrqACmaQA

Should you wish to contact the primary researcher for any further information, you may do so via the following contact email address:

Steven Ross

s.ross6@edu.salford.ac.uk

Should you wish to raise any concerns regarding the research then you can do so by contacting the Director of Studies on the following contact email address:

Dr John J McMahon

j.j.mcmahon@salford.ac.uk

Appendix 3.0 – Health Screening Form

Health Screening Questionnaire

1. Personal Information

Surname: Forename:
Date of Birth: Age
Height: Weight:

2. Additional Information
   a. Please state when you last had something to eat / drink:
   b. Circle the statement that relates to your present level of activity:
      Inactive Moderately active Highly Active
   c. Give an example of a typical weeks exercise:

   d. If you smoke, approximately how many cigarettes do you smoke a day?

3	Are you currently taking any medication that might affect your ability to participate in the test as outlined?	YES	NO
4	Do you suffer, or have you ever suffered from, cardiovascular disorders? E.g., chest pain, heart trouble, cholesterol etc.	YES	NO
5	Do you suffer, or have you ever suffered from, high/low blood pressure?	YES	NO
6	Has your doctor said that you have a conditioning that you should only do physical activity recommended by a doctor?	YES	NO
7	Have you had a cold or feverish illness in the last 2 weeks?	YES	NO
8	Do you ever lose balance because of dizziness, or do you ever lose consciousness?	YES	NO
9	Do you suffer, or have you suffered from, respiratory disorders? E.g., asthma, bronchitis etc.	YES	NO
10	Are you currently receiving advice from a medical advisor i.e. GP or Physiotherapist **not** to participate in physical activity because of back pain or any musculoskeletal (muscle, joint or bone) problems?	YES	NO
11	Do you suffer, or have you ever suffered from diabetes?	YES	NO
12	Do you suffer, or have you ever suffered from epilepsy/seizures?	YES	NO
13	Do you know of any reason not mentioned above, why you should not exercise e/g/. head injury (within the last 12 months), pregnant or new mother, hangover, eye injury or anything else.	YES	NO

Participant Signature:
Date:

Appendix 4.0 – Ethical Approval HSR1718-108

University of Salford MANCHESTER

Research, Enterprise and Engagement Ethical Approval Panel

Doctoral & Research Support
Research and Knowledge Exchange,
Room 827, Maxwell Building,
University of Salford,
Manchester
M5 4WT

T +44(0)161 295 2280

www.salford.ac.uk

6 September 2018

Dear Steven,

RE: ETHICS APPLICATION–HSR1718-108 – 'A cross-sectional comparison of hamstring and gluteal muscle surface electromyography (sEMG) and joint moments across bodyweight and externally loaded exercises.'

Based on the information that you have provided, I am pleased to inform you that ethics application HSR1718-108 has been approved.

If there are any changes to the project and/or its methodology, then please inform the Panel as soon as possible by contacting Health-ResearchEthics@salford.ac.uk

Yours sincerely,

Professor Sue McAndrew
Chair of the Research Ethics Panel

Appendix 5.0 – Ethical Approval 1594

E ethics

To: Steven Ross

Reply Reply all Forward

Thu 12/08/2021 10:00

Low importance

The Ethics Panel has reviewed your application: Practices and Perceptions of Hamstring Injury Prevention Training Across Sports and Practitioners
Application ID: 1594

The decision is: Application Approved.

If the Chair has provided comments, these are as follows:

Please use the Ethics Application Tool to review your application.

Appendix 6.0 – Ethical Approval 6651

ethics

To: Steven Ross

Cc: John Mcmahon

Fri 06/01/2023 14:15

Low importance

The Ethics Panel has reviewed your application: The Effects of Resistance Training and High-Speed Running on Markers of Hamstring Strain Injury and Athletic Performance.
Application ID: 6651

The decision is: Application Approved.

If the Chair has provided comments, these are as follows:

You will no longer be able to edit your application in the system.

Link to the Ethics Application Tool: https://apps.powerapps.com/play/de0240e7-3d59-4974-849e-ba87d2541856?tenantId=65b52940-f4b6-41bd-833d-3033ecbcf6e1