Evaluating and Developing Force Plate Practice for Monitoring Lower-Body Neuromuscular Function in Soccer

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
ATP	Adenosine Triphosphate
ACh	Acetylcholine
ANOVA	Analysis of Variance
AMTI	American Mechanical Technology Inc.
AS	Arm Swing
CVS	Cardiovascular System
COD	Change of Direction
COM	Centre of Mass
CMJ	Countermovement Jump
CNS	Central Nervous System
CK	Creatine Kinase
CV	Coefficient of Variation
CMRJ	Countermovement Rebound Jump
CT	Contraction Time
CI	Confidence Interval
DOMS	Delayed Onset Muscle Soreness
DTE	Delayed Training Effect
DJ	Drop Jump
DSI	Dynamic Strength Index
EFL	English Football League
EPL	English Premier League
EMG	Electromyography
ES	Effect Size
EPPP	Elite Player Performance Plan
FA	Football Association
FIFA	Fédération Internationale de Football Association
FT	Flight Time
FT:CT	Flight Time Contraction Time Ratio
FDP	Foundation Phase
GCT	Ground Contact Time
GAS	General Adaptation Syndrome

GPS	Global Positioning System
GRF	Ground Reaction Force
g	Gravitational Acceleration
HD	Hawkin Dynamics
HR	Heart Rate
HRV	Heart Rate Variability
HIIT	High-Intensity Interval Training
ID	Identification
ICC	Intraclass Correlation Coefficient
IMTP	Isometric Mid-Thigh Pull
IQR	Interquartile Range
JH	Jump Height
KPI	Key Performance Indicator
LOA	Limits of Agreement
MDT	Multi-Disciplinary Team
MSKS	Musculoskeletal System
MTU	Muscle Tendon Unit
MDC	Minimal Detectable Change
MVC	Maximal Voluntary Contraction
mRSI	Modified Reactive Strength Index
MAS	Maximal Aerobic Speed
MD	Match Day
NMS	Neuromuscular System
NMF	Neuromuscular Function
NTF	Neuromuscular Transmission Failure
NCAA	National Collegiate Athletic Association
NHST	Null Hypothesis Significance Testing
OLPR	Ordinary Least Products Regression
PAP	Post-Activation Potentiation
PAPE	Post-Activation Performance Enhancement
PDP	Professional Development Phase
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PCC	Population, Concept, Context

PHV	Peak Height Velocity
RSPS	Respiratory System
RJ	Rebound Jump
ROM	Range of Motion
RSI	Reactive Strength Index
RFR	Random Forest Regression
RFD	Rate of Force Development
S&C	Strength & Conditioning
SSC	Stretch-Shortening Cycle
SFRA	Stimulus-Fatigue-Recovery-Adaptation
SJ	Squat Jump
SEM	Standard Error of Measurement
SD	Standard Deviation
TOV	Take-Off Velocity
TL	Training Load
$VO_{2\,MAX}$	Maximal Oxygen Consumption
VJ	Vertical Jump
YDP	Youth Development Phase
YT	Youth Team

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ABSTRACT

The aim of this thesis was to evaluate and identify a best practice for force plate assessments for monitoring lower body NMF in soccer. It was evident following a literature review and scoping review that there is a variety of options for force plate testing application, but no general consensus on a best practice approach for the purpose of monitoring acute changes in NMF. The scoping review highlighted the CMJ and DJ tests as the most utilised in studies monitoring acute changes in NMF using force plates. From study 1, the HD Inc. wireless dual force plate system can be considered valid for collecting CMJ and DJ force-time data, because no fixed or proportional bias was present for any CMJ variable (N = 17) and was present for only 2 out of 18 DJ variables, where percentage differences were considered small when compared to a laboratory grade "gold standard" system. The mean effective fall height recorded during the DJ test was approximately 5 cm less than the prescribed 40 cm box height, which renders the DJ unsuitable as an assessment in physical profiling (i.e., for objective benchmarking) unless fall height can be established during trials. The utility of the CMRJ test (i.e., alternative RJ test where fall height is determined by a preceding CMJ) was investigated in study 2 following this determination. Acceptable test-retest reliability was demonstrated for 13 CMJ metrics for professional soccer players in the pre-season period in study 2 (a). Acceptable test-retest reliability was demonstrated for a limited number of CMJ (N = 5), DJ (i.e., only body weight and net braking impulse), CMRJ (i.e., only body weight and RJ portion net braking impulse) metrics and no IMTP metrics for youth soccer players in the pre-season period in study 2 (b). Acceptable test-retest reliability was demonstrated for 15 CMJ metrics for youth soccer players in the in-season period in study 2 (c). In study 3, a targeted sampling approach led to 7 professional EFL clubs with a total of 139 professional (age: 24 ± 5 years; height: 184 ± 7 cm; mass: 81 ± 9 kg) and 137 youth (age: 17 ± 1 years; height: 178 ± 17 cm; mass: 72 ± 8 kg) soccer players being recruited, where acceptable within-session reliability was demonstrated for 32 CMJ metrics, and 25 of these metrics discriminated between professional and youth soccer players in the pre-season period. Acceptable within-session reliability was demonstrated for all CMRJ CMJ portion (N = 5) and RJ portion (N = 25) metrics, and CMJ portion body weight and 20 RJ portion metrics discriminated between professional and youth soccer players in the pre-season period. Peak force and relative peak force derived from the IMTP test demonstrated acceptable within-session reliability and discriminated between professional and youth soccer players in the pre-season period. Out of the 15 CMJ metrics which demonstrated acceptable test-retest reliability in study 2 (c), 14 of these metrics demonstrated sensitivity to change and

thus utility for monitoring acute changes in NMF following a competitive, in-season, youth soccer match in study 4. Based on the body of work produced within this thesis, the author proposes the use of a combination of 10 (out of an applicable 28) CMJ metrics for different purposes. Specifically, jump momentum, mean propulsive power, and mean propulsive force may be applied concurrently for objective benchmarking and monitoring acute changes in NMF. Additionally, metrics such as mRSI, JH, relative mean propulsive power, and relative mean propulsive force may be utilised as objective benchmarks for professional and youth soccer players in the pre-season period, and metrics such as propulsive phase time, countermovement depth, and body weight may be utilised for monitoring youth soccer players' acute changes in NMF in the in-season period. From the key findings in study 3, practitioners may also utilise CMRJ RJ portion RSI, JH, jump momentum, mean propulsive force, relative mean propulsive force, mean propulsive power, and relative mean propulsive power, and IMTP peak force and relative peak force, for objective benchmarking for professional and youth soccer players in the pre-season period. A physical practitioner working in soccer can utilise the information presented within this thesis including test and metric selection, appropriate data collection and analysis procedures, statistical processes for determining objective benchmarks and observing meaningful change, and information regarding the practical application of these processes into real-world environments when utilising the wireless dual force plate systems.

Keywords

Sports Science; Strength and Conditioning; Biomechanics; Four Corner Model; Physical Corner; Preparedness; Profiling; Reporting; Statistical Analyses; Association Football.

1 INTRODUCTION

1.1 The Origins of Soccer

Association football, commonly referred to as soccer, is a global phenomenon and likely the most popular sport in the world. The reason for the sport's popularity may be multifactorial, including factors such as its historical origins, cultural significance, accessibility, and the globalisation of the game [1, 2]. The game of soccer originated in England in the mid-19th century and quickly spread across Europe [1]. It then gradually spread across the globe through British imperialism and colonization, becoming popular in countries such as Brazil, Argentina, and Uruguay [1, 2]. In such countries, soccer is not just a sport but a way of life and is deeply ingrained in national identity to express patriotism and pride [2]. For example, in Brazil, soccer is seen as a symbol of national unity and used to express Brazil's cultural identity [2]. Additionally, soccer is a sport that requires minimal equipment making it easy and affordable to play in many parts of the world. Soccer can be played in almost any open space making it accessible to people of all ages and skill levels. Because the sport is also played at an international level and televised globally, the ability to watch and follow international soccer has allowed fans to connect with the sport on a global level, further increasing its popularity. Soccer became organised with the foundation of the English Football Association (FA) in 1864, and the first Fédération Internationale de Football Association (FIFA) Men's World Cup™ took place in 1930 [3]. The FIFA World Cup™ is a quadrennial tournament which consists of 32 national teams from across the globe [4]. Throughout the tournament, every team will play a minimum of 3 matches, where teams that make it to the final will play a total of 7 games [4]. In 2022, the FIFA World Cup™ was held in the Middle Eastern sovereign and independent State of Qatar [4]. An original slogan proposed for this World Cup™ was "Expect Amazing", and the tournament lived up to expectations [4]. The tournament winners, Argentina, played their 7 games over a period of 26 days (average 3.7 days per game) from November 22nd to December 18th, 2022. The fixture frequency varied throughout each stage, with 3 (N =1), 4 (N = 3), 5 (N = 1), and 6 (N = 1) days seen between fixtures, highlighting the importance of efficient and effective recovery throughout this period.

As an example of the sport's global reach, 5.95 billion social media engagements were recorded from 93.6 million posts throughout this tournament [5]. A total 550 million global viewers watched the opening game where Ecuador beat hosts Qatar, whilst the Final, where Argentina prevailed victorious over France, entertained 1.5 billion people worldwide [5]. The tournament illustrated an increasing competitive level of competing nations, where a record 15 upsets (i.e., the underdog beat the favourite) was seen, the highest ever in FIFA World Cup™ history [6]. The tournament also highlighted the increasing high stakes and need for consistent optimal performance in matches because teams were more clinical than in any previous tournament. A record 172 goals were scored at this tournament, the highest since the tournament was expanded to 32 teams in 1998 (171 scored at both France 1998 and Brazil 2014) [6]. This was also achieved from only 1,458 shots (an average of 22.8 attempts at goal per match), which is the lowest recorded since the start of these statistics in 2002, with the previous low of 1661 shots recorded in 2014 [6]. Because of the constant pursuit for improvements in player quality globally, the consequences of individual mistakes have risen, and thus consistent optimal on-field performance is required. Accordingly, backroom staff work towards improvement in various aspects of performance with the aim to be successful in their respective campaigns [7]. This is also particularly important at the club-level, where teams competing in the English Premier League (EPL) gain more prize money yearly based on their finishing league position (+£2.2 million per finishing place) [8]. In the upcoming FIFA World Cup™ 2026, which will take place across North America (Canada, Mexico, and United States of America) from June 11th to July 19th, 2026, teams will have to conduct their physical preparations whilst travelling across multiple time-zones, as is also commonly seen in club-level continental championships (e.g., the Union of European Football Associations Champions League). Therefore, information regarding the most efficient and effective methods of preparing physically in this scenario would be useful.

1.2 The Multi-Disciplinary Team Approach

The English FA's Four Corner Model is a widely used framework for the development of soccer players (Figure 1.1) [9]. It was designed to provide a framework for coaches and trainers to develop soccer players in a holistic manner [10], including four key areas of development: technical/tactical, physical, psychological, and social [9].

The four key areas of development in this model are described below [9]:

- Technical/Tactical: This includes the development of soccer-specific technical skills such as dribbling, passing, and shooting, and tactical awareness.
- Physical: This includes the development of physical field-based attributes such as speed, agility, and strength using appropriate means of physical evaluation and training.
- Psychological: This includes the development of mental attributes such as confidence, motivation, and resilience.

- Social: This includes the development of social attributes such as communication, teamwork, and leadership.

Figure 1.1. English Football Association's "Four Corner Model" of sports performance [9].

To support the FA Four Corner Model and the development of soccer players, multi-disciplinary teams (MDTs) are formed in soccer clubs, but the structure can vary depending on the level of play and resources available. However, the core elements of these teams are typically composed of professionals from different disciplines, such as [9]:

- Coaching staff: This includes technical and tactical coaches, such as head coaches, assistant coaches, and specialized coaches for specific aspects of the game.
- Physical performance staff: This includes staff responsible for optimising (i.e., conducting assessments for monitoring and developing) physical preparedness (e.g., sports scientists, Strength & Conditioning (S&C) coaches, sports nutritionists), and recovery from injury (e.g., physiotherapists, sports rehabilitators, athletic trainers, etc.) and illness (e.g., doctors).

- Support staff: This includes staff who focus on mental preparedness for optimal performance (i.e., sports psychologists), and other professionals who provide mental health and well-being support to players and their families (e.g., social workers).

MDTs are considered essential in providing comprehensive holistic support to soccer players for improving personal development and "sports performance" [11].

1.3 Background of the Physical Corner

Based on the FA Four Corner Model and MDT approach, the overarching objective to "*improve sports performance*" in soccer relies partially on the improvement of physical characteristics, alongside the abovementioned technical/tactical, psychological, and social components (Figure 1.1) [9]. The purposeful, efficient, and effective locomotion of the human body is a requirement in many sports, therefore, the objective of the "*physical corner*" is to optimise the "*physical preparedness*" of the musculoskeletal system (MSKS), neuromuscular system (NMS), cardiovascular system (CVS), and respiratory system (RSPS) to enhance the potential for an athlete to perform at their physical optimum, to increase the chances of outperforming their opponents, reduce the likelihood of non-contact injury, and increase the potential of achieving sporting success [12]. The optimal function of these systems is critical to key physical attributes of soccer (i.e., which contribute to goal-scoring chance creation and defending), such as linear sprinting speed, acceleration and deceleration capability, change of direction (COD) speed, agility, jumping ability, and aerobic and anaerobic endurance [13]. Specifically, lower-body neuromuscular strength and power capabilities (relative to body mass) have been reported to underpin the performance of such attributes in soccer players [14], which is understandable given the production of force relative to mass determines acceleration [15], yet this force must be produced with limited ground contact times (GCTs) in soccer (e.g., <150 ms during high speed running [16]) and when reacting quickly to external stimuli. The development of flexibility, coordination, and proprioception might also contribute to efficient locomotion, injury mitigation, and benefit overall performance [11]. A differing amount of importance is placed on each of these attributes dependent on playing position in soccer, however, athletes must succeed in most of these parameters to overcome their opponents in as many instances as possible [17].

1.3.1 A Process of Practice for the Physical Corner

It is the responsibility of the physical coach to apply the understanding of (a) the physical preparedness of the body's systems, (b) the principles of the fitness-fatigue model, and (c) how to practically apply these principles within soccer, to inform subsequent practice in the physical corner. *Points (a) and (b) are discussed further in the literature review.* Regarding point (c), the requirement of the physical coach is to produce a needs analysis of the sport (including a coach's playing style and philosophy), accumulate objective information on each athlete's individual physical preparedness, and design and implement periodised physical training programs focused on developing physical on-field attributes (Figure 1.2) [18]. The information from points (a) and (b) feeds into the individual player "profile", which informs subsequent practice via a process of evaluation, reports which inform training direction, and a continuous review of progress (Figure 1.2). To illustrate this further, practice within the physical corner can be characterised into 4 stages:

1) **Profile:** Having a general understanding of physical preparedness and the fitness-fatigue model (as stated above), physical needs analysis of the specific sport (physical requirements of the body's systems), information of the individual athlete (sex, age, playing position, role, event, etc.), and the individual athlete's/sports club's objectives,
2) **Evaluate:** The thorough identification (ID) of strengths and weaknesses (talent ID and benchmarking) through fitness testing relative to the profile (generally performed every 10-12 weeks),
3) **Report:** The prescription, reduction, or removal of informed physical training interventions based on the evaluation reports, and
4) **Review:** The re-testing of physical preparedness (e.g., a smaller testing battery performed every 4-6 weeks) to determine changes in fitness, and the continuous acute monitoring (e.g., on a weekly and/or daily basis) of fatigue to renew context for informing training direction, and the prescribed acute recovery methods [19].

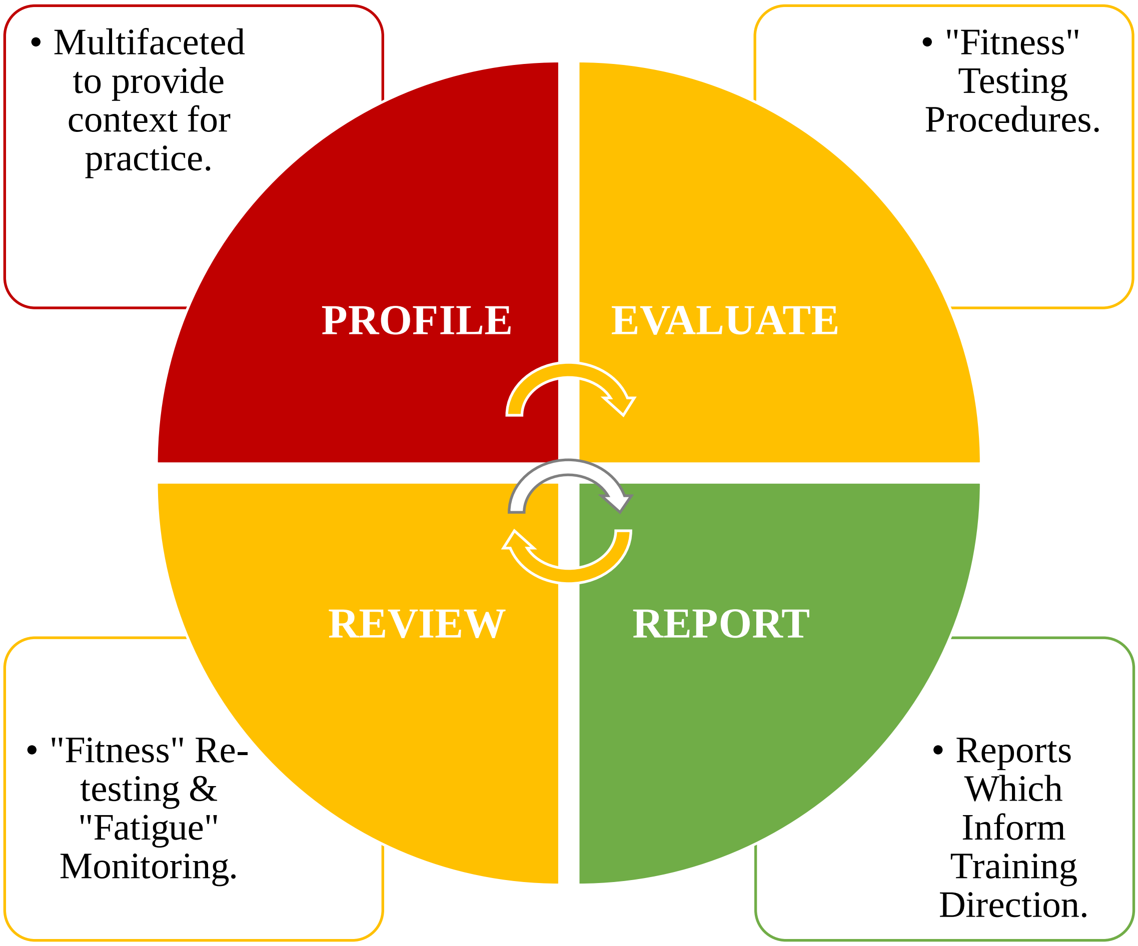

Figure 1.2. Example process of practice for the physical corner.

This whole process should be cycled 3 times per season (i.e., pre-, mid-, and end of-season) in soccer. However, stages 3 and 4 should be cycled on a more frequent basis, with the review process consisting of smaller scale fitness testing batteries (e.g., every 4-6 weeks) informing short-term training direction, and the results from weekly and daily fatigue monitoring informing immediate recovery requirements and the length and mode of recovery strategies adopted. Where this process is considered 'optimal' for physical coaches to adopt, utilising such information to inform training direction is something that is often done inconsistently or overall, quite poorly in soccer, traditionally due to a lack of understanding or ability to make change within a club. Thus, the literature review in chapter 3 considered this process by addressing components related to physical profiling, evaluation methods, and data reporting and reviewing procedures, and this thesis overall aimed to promote the integration of this process in practice by determining a best practice for evaluation methods and data reporting and reviewing procedures in soccer.

1.4 Force Plate Technology

Recent developments in force plate systems facilitate an opportunity to gain informative data on neuromuscular function (NMF) in practical real-world settings due to their robustness, practicality, and thus feasibility. Specifically, developments in force plate hardware (e.g., the production of wireless and portable systems) has eliminated restrictions posed by traditional wired force plate systems where data collection has been previously limited to laboratory settings. Recent developments in proprietary software have also enabled practitioners to receive valuable data from force plate tests immediately post-test, and without having to develop an advanced skill set in data analysis using software such as Microsoft Excel, MATLAB, or R [20]. The world's first wireless dual force plate system with proprietary software, which automatically calculates a range of variables (e.g., jump height [JH], peak and mean force and power, etc.) across several tests (e.g., single and multi-joint dynamic and isometric tests) and reports data immediately after the test has been conducted, was recently developed by HD Inc. (Westbrook, ME 04092, USA). Despite improved feasibility in these hardware and software developments, practical technological solutions must also provide accuracy in measurements, and the HD Inc. system boasts validated hardware [21] and software [20] against criterion methods. Such technological developments have contributed to an increased popularity of force plate testing in professional sports environments with many S&C coaches testing their athletes daily [22], however, how to best utilise force plates in practice to monitor NMF and inform decision making is yet to be realised. This is due to a lack of research on how best to integrate such technology when conducting multiple force plate tests (e.g., dynamic assessments and isometric assessments), with appropriate data collection and analysis methods, and in real-world settings, to provide a comprehensive streamlined approach which can be applied for both profiling and monitoring changes in athletes' lower body NMF.

In a recent scoping review, Guthrie et al. [23] identified previously utilised methods of longitudinally evaluating NMF in the football codes, reporting that NMF was most commonly evaluated utilising force plate tests such as the countermovement jump (CMJ; N = 11), squat jump (SJ; N = 2), and isometric mid-thigh pull (IMTP; N = 2) tests. Amongst the assessments of NMF identified in the study, such as JH (N = 9), peak power (N = 3), peak force (N = 2), flight time (FT; N = 2), and flight time contraction time ratio (FT:CT; N = 2) were the most frequently reported metrics. Although metrics collected from proprietary software are often well defined, data processing and analysis procedures should be of primary interest to users to maximize confidence in results and avoid inaccuracies in information due to data processing and analysis errors [20]. Examples include metric definitions (i.e., concentric vs propulsive)

[20], metric calculations (i.e., time bands vs average or peak rate of force development [RFD]) [24], phase identifications (i.e., rules for identifying the start and end of each phase) [25], and the process of forward dynamics integration (i.e., the mathematical process of obtaining acceleration-, velocity-, and displacement-time data from force-time data) [20, 25]. For example, Merrigan et al. [20] identified that the braking and propulsion phases of a CMJ test (i.e., as described in the HD Inc. software) have been described as the eccentric and concentric phases, respectively, in other commercially available force plate software. The braking phase has also been referred to as the eccentric phase in published research [26-28], potentially based on the assumption that the leg extensor muscles are actively lengthening (i.e., working eccentrically) to decelerate the body's centre of mass (COM) during this phase [25]. However, the collection and analysis of vertical force-time data using force plates only provides insight into the kinetics and kinematics of linear COM motion and cannot inform us as to what is occurring at the joint or muscle tendon unit (MTU) level [25]. Additionally, it is not only the leg extensors that contribute to the CMJ test, and it would be incorrect to assume that all lower-body MTUs are working eccentrically during the braking phase (e.g., the medial gastrocnemius may shorten during this phase [29]).

Comfort et al. [30] described some key considerations for testing selection including the relationship between the performance in specific test metrics and sports actions (e.g., sprint speed) [31-35], the validity and reliability of specific tests and metrics [36], the availability of normative data and benchmarks for specific tests [30], and the feasibility of test application relative to the available facilities and equipment [23]. These considerations are discussed further in the literature review in chapter 3 and explored throughout this thesis. Often in normative data studies [27, 37-39] the reported data only represents the average of the population used, which limits the ability to determine what is a "good" performance within a cohort [40]. Objective benchmarks serve this purpose, yet measures are only applicable if they discriminate between two groups of interest (e.g., different competitive level and/or age category). However, age comparisons of normative data in professional English football clubs are only available for a variety of force plate tests in female youth soccer players [37, 38], and available for only the IMTP in male youth soccer players [39]. Additionally, when conducting physical performance tests on a frequent basis (e.g., weekly or daily "fatigue" monitoring) to immediately inform training direction or recovery processes, simply observing a raw value increasing or decreasing via central tendency statistics (e.g., mean, median, or mode) is not the recommended approach to determining difference [41]. While Null Hypothesis Significance Testing (NHST; e.g., t-tests and Analysis of Variance [ANOVA]) has been utilised to inform the statistical significance of a reported change in performance scores [42-49], it does not inform as to a "real" or "meaningful" modification in performance by considering the reported change relative to random measurement error within the test [50]. Commonly, effect sizes (ESs) are utilised alongside NHST in empirical studies to inform the magnitude of a reported change in performance scores [51]. When investigating standardised mean differences (e.g., when determining discriminations between two groups of interest), the d family of ESs (e.g., Cohen's d, and Hedge's g) are suitably applied for a comparison between the mean difference between observations divided by the standard deviation (SD) of these observations [51]. The use of ESs also extends beyond this, where they can be of benefit to further research such as when forming meta-analyses and comparing standardized ESs across studies, and for use in an a-priori power analysis when forming a new study [51]. On an individual subject basis (e.g., when determining acute change), determining "meaningful" change can also be achieved via the utilisation of statistics such as the minimal detectable change (MDC) [50], however, a lack of utilisation of the MDC approach is seen within research focused on monitoring acute changes in NMF [42, 52-56].

1.5 Summary

An increase in the popularity and globalisation of the game and improvements in coach education has led to developments in player technical ability and managerial tactical nous in recent times. Resultantly, the physical demands of today's game (i.e., typical external workloads) are high, and players work to continuously push the boundaries of individual physical preparedness (i.e., develop the internal response) to compete at the highest levels. To achieve this, physical coaches (i.e., sports scientists and S&C coaches) play a critical role in helping soccer players by providing evidence-based recommendations for physical training. This can be achieved by having a foundational understanding of physical preparedness in soccer, objective information about the physical demands of the sport, and an ability to monitor the physical capabilities of players. The latter can be performed via a range of scientific methods such as biomechanical analysis and physiological testing to assess players' physical preparedness, identify areas for improvement, and monitor changes over time [18]. Athletes can be accurately tested using robust and practical procedures within a few minutes and coaches can gain immediate access to their athletes' scores when utilising the HD Inc. force plate system [21]. Knowledge of the best practice of utilising force plates (e.g., testing protocols, data analysis procedures, etc.) is essential to optimising impact, and it was the focus of this thesis to investigate and enhance this knowledge base and provide objective benchmark data.

2 AIMS AND OBJECTIVES

The overarching aim of the proposed work is to evaluate and develop force plate practices for monitoring lower body NMF in soccer. Through reading this thesis, it is intended that a practitioner would take away a best practice process of force plate testing including test and metric selection, appropriate data collection and analysis procedures, statistical processes for determining objective benchmarks and observing meaningful change, and information regarding the applications of these aspects into real-world practice. Objectives were designed to achieve this aim including producing information regarding the validity (chapter 6) [21, 57], reliability (chapters 7 and 8) [58-61], meaningfulness (relation to sports specific actions; chapter 8) [32, 62-64], discriminatory capabilities (i.e., for objective benchmarking; chapter 8) [27, 37-39], and sensitivity to change (chapter 9) [42] of specific metric types (e.g., outcome, strategy, kinetic, and ratio measures) across a range of force plate tests with the HD Inc. dual force plate system. Specifically, the CMJ test was a prominent feature of this thesis, because it:

- Requires minimal familiarisation, is quick to perform, and is relatively non-fatiguing.
- Provides theoretically meaningful information for the evaluation of lower-body Stretch-Shortening Cycle (SSC) function.
- Has demonstrated consistently good between-trial reliability (coefficient of variation [CV] ≤ 10%) for a variety of metrics [65-67].
- Has demonstrated an ability to discriminate between age categories [27, 37, 38].
- Is the most popular test prescribed to assess neuromuscular fitness and fatigue (preparedness) developments following physical training in the football codes [23].

It was hypothesised that the CMJ test would be proposed in the summary of best practice at the end of this thesis due to its greater reliability and ease of application over other force plate tests, such as variations of rebound jump (RJ) tests and isometric strength tests, in both adult and youth soccer populations.

2.1 Project Plan

This thesis was developed via five studies with objectives which can be characterised as relating to either review, evaluation, or development aspects of research.

PROJECT STAGE 1: REVIEW (OF METHODS)

Scoping Review

First, information from previous investigations must be collated and critically appraised, to determine common themes and gaps in the research. This information was then used to construct the methods of further investigations (e.g., study design, test, and metric selection).

Scoping Review of Methods of Monitoring Acute Changes in Lower Body Neuromuscular Function via Force Plates

Objectives To identify, map, and describe which practices exist in the context of monitoring acute (<1 week pre- to post-physical stimulus) changes in NMF using force plates. In a qualitative manner, the review described the similarities, differences, and gaps in the body of evidence retrieved regarding study design and the specific force plate data collection and analysis procedures employed.

PROJECT STAGE 2: EVALUATION (OF METHODS)

Study 1

Secondly, it is important that the equipment used for these investigations is accurate. If this has not been previously determined, it is critical to confirm this to ensure confidence in each study's results.

The Validity of Hawkin Dynamics Wireless Dual Force Plates for Measuring Countermovement Jump and Drop Jump Variables

Objective: To evaluate system accuracy (concurrent validity of the HD Inc. hardware) of data derived from a laboratory-grade, in-ground force plate system (i.e., a "gold standard").
Hypothesis: Agreement would be found between the force plate systems for all variables with no fixed or proportional bias present.

Study 2

Thirdly, it is vital to evaluate commonly used and theoretically meaningful force plate tests and metrics to determine which hold the greatest reliability for the detection of acute changes in NMF, in soccer athletes.

Test-Retest Reliability of Countermovement Jump, Drop Jump, Countermovement Rebound Jump, and Isometric Mid-Thigh Pull Force-Time Variables in Soccer Athletes

Objective: To evaluate the test-retest reliability of common force plate tests and metrics in soccer athletes.

Hypotheses: Reliability would be better for propulsive- over countermovement-phase (i.e., unweighting and braking phase) force-time metrics in vertical jumps (VJs), better for the adult versus the youth soccer players in the pre-season period, and better in-season compared to pre-season in youth soccer players, based on previous studies results [65, 68-70].

PROJECT STAGE 3: DEVELOPMENT (OF PRACTICE)

Study 3

Within- and between-squad comparisons of physical capacity are often performed in soccer in the talent ID/benchmarking process (i.e., "profiling"), the collation of normative data, identification of discriminatory capabilities between age categories, and development of data reporting procedures for producing objective benchmarks using established reliable tests and metrics would be useful for future research and practice.

Normative Data and Objective Benchmarks of Force Plate Tests for Professional and Youth Soccer Players in the English Football League

Objective: To establish normative data and objective benchmarks for key CMJ, countermovement rebound jump (CMRJ), and IMTP metrics in professional and youth soccer players in the EFL League 2 and investigate age-specific statistical differences between groups.

Hypotheses: Professional soccer players would produce significantly greater outcome performances (e.g., JH) in jump tasks than their youth counterparts through the greater expression of relative kinetic output, but through similar movement strategies, and greater isometric absolute, but not relative, strength in line with previous findings [37-39].

Study 4

Finally, taking what has been learned of the reliability of specific tests and metrics for the monitoring of acute changes in NMF and applying this in a real-world setting with soccer athletes is essential.

Monitoring Acute Changes in Countermovement Jump Neuromuscular Function in Soccer Athletes

Objective: To evaluate the effectiveness of force plate methodologies for monitoring acute changes in lower-body NMF due to in-season competitive match-pay, via the CMJ test performed on force plates, in youth soccer athletes.

Hypotheses: A reduction in body mass would be seen from pre- to post- a competitive soccer match, likely due to fluid loss via perspiration. Reductions in kinetic measures (e.g., mean propulsive force, jump momentum [equal to net propulsive impulse]) would be seen. However, a reduction in both aspects means that mass relative outcome measures (e.g., take-off velocity [TOV; equal to relative propulsive impulse] and JH) might have been unchanged.

3 LITERATURE REVIEW

As per the process of practice described in Figure 1.2 in section 1.3.1. A Process of Practice for the Physical Corner, physical coaches commonly work through a four-step process of profiling, evaluation, reporting, and reviewing physical information for athletes. In this literature review, information regarding the formulation of a physical profile such as general knowledge of physical preparedness, the fitness-fatigue model, and the physical requirements of the body's systems in soccer is provided in section 3.1. Theories of Physical Preparedness, 3.2. Physical Preparedness in Soccer, 3.3. Applying Theory to Practice, 3.4. Key Mechanisms of the Neuromuscular System, and 3.5. Neuromuscular Fatigue. Then, information regarding evaluation methods for "fitness' testing and "fatigue" monitoring is provided in section 3.6. Evaluating Neuromuscular Function and 3.7. Evaluation Procedures, and information regarding reporting procedures is provided in section 3.8. Reporting and Reviewing Procedures.

3.1 Theories of Physical Preparedness

Different theories exist relating to the optimisation of physical preparedness. The original theory of physical preparedness is the General Adaptation Syndrome (GAS) theory [71, 72], proposed by Hans Selye in 1956 [71, 73], which states that all stress (e.g., via physical activity) results in the same consequence; an "alarm" stage which initially negatively impacts physical preparedness, followed by a "resistance" stage where physical preparedness gradually returns to normal or possibly greater than before, known as supercompensation, and that these factors share a general cause and effect relationship for all forms of physical activity [72, 74]. It is proposed that the initial response, or alarm phase, is due to an accumulation of fatigue that results in a reduction in performance capacity [73], and the resistance phase is often known as a traditional recovery period. In the context of exercise, fatigue refers to a combination of both neural and contractile impairment [72, 74]. These factors are discussed further in section 3.5. Neuromuscular Fatigue. If the intensity and/or duration of physical activity is too great for the individual, and/or training is repeated too frequently without sufficient recovery over a prolonged duration, this can lead to a gradual decline in capacity over time, termed the "exhaustion" stage [73].

Although not originally conceptualized for physical training, the GAS model has been a common concept used to develop theories on training periodization [73]. Contrary to this, authors have recommended an emphasis be placed on the design and implementation of responsive training programmes that facilitate the emergence of context-specific training-planning solutions to better accommodate contemporary elite practice [75]. More recently, the

Stimulus-Fatigue-Recovery-Adaptation (SFRA) theory (an extension of the GAS) also suggests that training stimuli produces a general response, but instead is influenced by the overall magnitude of the training stressor, thus influencing the body's adaptation. The theory proposes that the greater the magnitude of the workload encountered, the more fatigue accumulates and the longer the delay before complete recovery and adaptation can occur [73]. The theory also describes that while recovery is an important part of the training process, it is not always necessary to reach a state of complete recovery before engaging in a new bout or session of training, as long as it is planned responsibly [73]. The GAS and SFRA theories have been used in periodisation models specific to achieving sustained long-term developments in physical preparedness, where multiple bouts of physical activity, resulting in multiple alarm and resistance stages, are performed periodically aiming to optimise the supercompensation phase and minimising the exhaustion phase by periodically reducing the intensity, volume, and frequency of activity [76, 77].

The most current and prevailing theory of physical preparedness is the *fitness-fatigue model* [72, 74, 78], originally proposed by Zatsiorsky [73], which suggests 2 consequences of physical activity; a *fitness* response which is positive, and a *fatigue* response which is negative, and that both factors share an inverse relationship. The state of fitness of the body's systems without induced fatigue represents an individual's baseline level of physical preparedness [72, 74]. The fatigue response is considered to be large in magnitude with a brief duration, which results in an initial (acute) decrease in physical preparedness (similar to Selye's alarm stage) [73, 74]. In contrast, the fitness response is considered to have a shallow magnitude with a long (chronic) duration, which results in a return and supercompensation of physical preparedness over time (similar to Selye's resistance and supercompensation stages), given sufficient recovery from fatigue [73, 74]. According to this theory, physical preparedness is optimised with training regimes which can enhance fitness to the greatest extent and/or with the least amount of accumulated fatigue, which rationalises the physical coach's desire to optimise physical preparedness by increasing fitness long-term (chronically) and minimising fatigue in the short-term (acutely) [73, 74]. Additionally, it has been suggested that fatigue dissipates at a faster rate than fitness, thus allowing physical preparedness to become elevated if appropriate training strategies are used to retain fitness whilst recovering from fatigue [73]. Similarly, strategies can be employed to induce acute performance enhancements where desired, traditionally known as Post-Activation Potentiation (PAP) [79]. More recently, it has been discussed that PAP refers more to a change mechanistically, which has traditionally been assessed via changes in electrically evoked muscle twitch [80]. Oppositely, Post-Activation Performance Enhancement

(PAPE) is considered a better term referring to changes in overall performance (i.e., changes in voluntary systemic force and power output) [80-84].

An acute representation of the traditional fitness-fatigue model is resistance priming [85], which is considered a more chronic form of PAPE, as it manifests beyond the associated timeframe of PAPE [86]. Specifically, the time course for neuromuscular enhancement and dissipation occurs across periods lasting 6–48 hours after the completion of the priming activity [86]. In comparison, PAPE occurs over minutes, which means that some key mechanisms that occur following PAPE (e.g., muscle temperature and high-frequency motor neuron activation) are unlikely to have an effect following priming across a period of 48 hours. Priming is commonly prescribed utilising a micro-dosing approach, with low-volume strength (e.g., 3 sets of 3 repetitions of ~85% 1 repetition maximum [1RM] back squats) or power (e.g., 3 sets of 5 repetitions of 30–40% 1RM loaded CMJs) training stimuli most frequently implemented 8 hours before competition [87], yet can be applied <48 hours before competition, to improve subsequent multidirectional on-field performance [86]. Additionally, the fitness-fatigue model states that different physical activity will result in different fitness and fatigue responses from the body's systems, highlighting the "sport specificity" of the objective to optimise physical preparedness [73, 74]. This is important in soccer, where an optimal weekly schedule would consist of both field- and gym-based physical training regimens aimed at developing various physical attributes. For example, responses to strength- and power-based training may be more evident in the MSKS and NMS, with general responses in fitness including development in muscle cross-sectional area, muscle contractile protein composition, and muscle metabolic enzyme concentrations [88-91]. In comparison, responses to endurance-based activity would differ, where a more marked response would be seen in the CVS and RSPS with general responses in fitness including the development in maximal oxygen consumption ($VO_{2\ MAX}$), mitochondrial density, and muscle capillarization, as a few examples [92].

3.2 Physical Preparedness in Soccer

External workload (sometimes referred to as "volume") refers to the external physical output performed by players during soccer matches, including system movement distance and velocity [74]. Understanding the external workloads of professional soccer players is essential for designing effective training programs that prepare players for the demands of competition. This is commonly measured in soccer via players wearing Global Positioning System (GPS) devices [74, 93], which is a satellite navigation network initially developed for military purposes to provide precise location and time information of the tracking device [93]. With recent developments in GPS technology these systems are now much more practical, resulting in their use in athlete tracking and load quantification [93, 94]. The authors of several studies have investigated the external workloads of professional soccer players in the EPL, demonstrating a considerable amount of ground covered and the performance of many high-speed efforts during matches. Whilst it has been reported within an elite-level competitive soccer match a player will perform low-intensity activities for more than 70% of the game [95], Bradley et al. [17] found that EPL players covered an average total distance and high intensity running distance (≥19.8 km/h) of 10722 ± 978 m and 929 ± 305 m, respectively. Russell et al. [96] also found that players covered an average total distance and high intensity running distance (≥19.8 km/h) of 9457 ± 769 m and 487 ± 202 m, respectively, per match during the 2013–14 reserve team EPL season. The difference in external workloads between these studies may highlight a difference between the EPL senior and reserve levels.

External workloads can vary considerably between different playing positions and tactical styles. For example, Bradley et al. [17] reported the greatest total distance covered in a match was by wide (11612 ± 803 m) and central (11445 ± 647 m) midfield players, compared to central defenders who covered the least (9816 ± 567 km) distance per match, in the EPL. A similar pattern was reported for high intensity running (≥19.8 km/h) distance covered, where wide midfielders and central defenders covered the most (1214 ± 248 m) and least (612 ± 151 m) distance, respectively, in the EPL [17]. In a separate study, Bradley et al. [97] assessed the difference in external workloads performed by low-possession (46 ± 4% of ball possession) vs high-possession (55 ± 4% of ball possession) EPL teams. The authors reported that despite no difference being present in overall high intensity distance covered (938 ± 311 m vs 931 ± 299 m, respectively), a significant ($p < 0.01$) difference was determined in high intensity (≥19.8 km/h) distance covered whilst in- (343 ± 236 m vs 449 ± 266 m, respectively) and out- (539 ± 177 m vs 423 ± 153 m, respectively) of possession [97]. Based on these results, it seems as though EPL teams cover similar high intensity distance within a match when competing against one another. This is because the team which plays with a more ‘possession-based’ tactical style of play covers a greater amount of high-intensity distance with the ball in possession, which causes the opposition to match this high-intensity distance whilst out of possession, to try to defend advances to their goal and regain possession [97]. However, it is important to note that the retention of ball possession is difficult, as it requires exceptional technical ability and tactical application. The information presented in these articles suggests that individual external workload performed in a soccer match varies dependent on the position played and the tactical approach of the competing teams, but one must also consider capturing the demands of accelerations and decelerations as these also contribute to total volume.

Like the discussion of external workloads, researchers have shown that internal workloads of professional soccer players in the EPL can vary greatly depending on the position played, the type of training or match played, and individual player characteristics. Internal workload (sometimes referred to as "intensity") refers to the individual's physiological response to the external workload performed during training and matches, commonly measured using heart rate (HR) monitoring [98]. Previous reports indicate that the average HR during an elite soccer match is around 85% of maximal values, and the average oxygen uptake is around 70% $VO_{2\ MAX}$ [95, 99]. From a fatigue perspective, this would primarily tax the CVS and RSPS [12]. However, this internal response is likely due to an average of 150 – 250 brief intense actions (e.g., accelerations and decelerations) performed sporadically per match [95, 99], which induces a considerable amount of mechanical and metabolic fatigue in the NMS and MSKS [100, 101]. Mechanically, the heavy reliance on eccentric actions (e.g., during decelerations) can induce a considerable amount of muscle damage [79, 102] which contributes to Delayed Onset Muscle Soreness (DOMS) experienced following exercise (a sudden increase in these actions would be required for this to occur in sufficiently conditioned athletes) [103], and bioenergetically, requires the rates of creatine phosphate utilisation and glycolysis to be frequently high during a competitive match, with muscle glycogen probably the most important substrate for energy production in this sport [103]. It has been reported that muscle glycogen is reduced by 40-90% during a competitive soccer match [99]. With a reduction in the number of substrates available, the conversion to and the supply of Adenosine Triphosphate (ATP) is limited [103]. Metabolically, the utilisation of glycolysis to form ATP produces by-products such as lactic acid (i.e., a surplus of lactate and hydrogen ions [H^+]) and inorganic phosphate [104], which causes acidosis (i.e., lowering of blood pH) [99, 105], and can impair muscle contractility due to inhibition of enzymes reducing the rate of metabolic actions [2, 5]. In a non-professional friendly soccer match, it was reported that average fourfold increases (to around 4 mmol/kg wet weight) in muscle lactate were seen in players from resting values to after intense periods of play, with the highest value reported being 10 mmol/kg wet weight [99].

Fatigue mechanisms work in different combinations, magnitudes, and timeframes throughout a competitive match (Table 3.1). For example, fatigue immediately after periods of intense exertion in a soccer match does not appear to be linked directly to the breakdown of creatine phosphate, muscle glycogen concentration, lactate accumulation, or acidity (i.e., bioenergetic and metabolic processes), but instead to disturbances in muscle ion homeostasis and an impaired excitation of the sarcolemma (i.e., neural processes) [106]. At the initial phase of the second half, soccer players' ability to perform optimally is inhibited primarily by lowered muscle temperatures due to 15 minutes of inactivity [95, 103, 106]. Towards the end of the game fatigue sets in due to the confounding impacts of muscle damage (i.e., mechanical processes), low glycogen concentrations in a considerable number of individual muscle fibres, which is concurrent with a progressive increase of blood free-fatty-acids to compensate for a progressive lowering of muscle glycogen [95, 103, 106], and the accumulation metabolic by-products [107] such as H^+, inorganic phosphate, and ADP [104], which can cause acidosis (i.e., lowering of blood pH) [105] and impair muscle contractility (i.e., bioenergetic and metabolic processes) [2, 5]. Following a competitive match (e.g., 24 to 48 hours post-match), the accumulation of fatigue in these mechanical, neural, bioenergetic, and metabolic processes would contribute to a Delayed Training Effect (DTE), DOMS, and resultant impairment of NMF [19]. Sustained high intensity work rates during match-play inflicts a thermal strain on players and a physiological adjustment for the purposes of heat dissipation. Specifically, perspiration during a 90-minute soccer match results in an average body weight (via fluid) loss of adult male soccer players of ~2%, an amount been associated with decrements to cognitive psychomotor function, increases in core temperature, cardiovascular strain, a decreased blood volume, and exercise performance [108]. The mechanisms specific to *neuromuscular* fatigue in soccer are discussed further in section 3.5. Neuromuscular Fatigue. Methods previously utilised for evaluating NMF are discussed further in section 3.6. Evaluating Neuromuscular Function, and 3.7. Evaluation Procedures.

Table 3.1. Example Neuromuscular Impairment Mechanisms and Timeframes During and Following a Competitive Soccer Match.

Type	Mechanism	Timeframe
Central (Neural)	Disturbances in muscle ion homeostasis and an impaired excitation of the sarcolemma.	Immediately after intense periods of intense exertion.
Peripheral (Contractile)	Lowered muscle temperatures.	Immediately following the half-time interval.
Peripheral (Contractile)	Muscle damage.	Towards the end of the competitive match (with effects < 72 hours post-match).

Bioenergetic	Low muscle glycogen concentrations and concurrent increase of blood free-fatty-acids.	Towards the end of the competitive match (e.g., 75 to 90 mins, dependent on pre-match muscle glycogen content).
Metabolic	Accumulation of metabolic by-products (e.g., H^+, inorganic phosphate, and ADP), and resultant acidosis (i.e., lowering of blood pH).	Towards the end of the competitive match (e.g., 75 to 90 mins), but will also occur transiently following high intensity bouts interspersed with lower intensity activity.
Combination	DTE and delayed onset of muscle soreness.	~24 to 48 hours post-match.

The results of the discussed studies suggest that professional soccer players are subject to high overall (i.e., external and internal) workloads, which can vary greatly depending on a range of factors. For example, different physical stimuli (i.e., field- vs gym-based training) will manifest their own individual fitness and fatigue aftereffect response [73]. Additionally, a difference in individual responsibilities (i.e., playing position) during a competitive match can affect individual external workloads. Relating to internal workload, these same factors will also not uniformly produce alterations in physical preparedness for all athletes with different individual physical capacities, resulting in non-uniform changes in the physical preparedness of players within a squad [95, 103, 109]. This poses a challenge for physical coaches to determine individual developments in fitness, the accumulation of fatigue, and ultimately changes in physical preparedness. The accurate quantification and monitoring of physical preparedness can aid in this process and inform the resultant periodised planning of recovery and training.

3.3 Applying Theory to Practice

Fatigue is inevitable during physical activity which provides an appropriate overload stimulus to achieve a fitness response, which is essential as per the principles of periodisation and progressive overload [72, 74]. In fact, periods of training which accumulate greater fatigue are required to facilitate specific adaptations. Training intensity and volume are key drivers for physical adaptation and so in sports with less restricted competitive schedules (e.g., bodybuilding) planned over-reaching and the fatigue resulting from this (e.g., muscle damage and metabolic stress) is advantageous [73, 79]. In this situation, a reduction in physical preparedness is desired acutely to benefit an athlete's physical development chronically.

Alternatively, if a coach was to "back off" because athletes demonstrated signs of fatigue, they may hinder long-term fitness developments [19]. Despite this knowledge, minimising fatigue in the acute term and thus reducing the required amount of recovery is an approach often adopted in sports with a congested fixture schedule (e.g., soccer) [73, 74, 110]. This approach is typically termed as applying the "minimum effective dose" (also sometimes termed "minimum retention dose"), which would be advantageous in sports aiming to *maintain* physical preparedness, but as described, is prescribed usually at the sacrifice of optimal chronic long-term developments in fitness [73, 74]. A reduction in physical preparedness can immediately effect on-field physical performance and/or increase the potential for non-contact, soft-tissue injuries, but soccer athletes are required to compete again with minimal recovery time (e.g., 48 to 72 hours later) due to congested fixture schedules [72, 74, 110]. Because of this, difficulty can be found in designing long-term periodised programmes for soccer athletes which desire both chronic fitness developments and the minimisation of acute fatigue (e.g., in youth soccer). Such a programme might consist of mesocycles which aim to enhance specific aspects of fitness throughout a season (e.g., pre-season), and others which aim to "maintain" fitness whilst managing fatigue and optimising recovery during specific congested periods (e.g., in-season) [72, 73].

3.4 Key Mechanisms of the Neuromuscular System

Of particular interest to this project, the NMS's function is to facilitate and control the movement of the human body. This is achieved under the central command of the cerebral cortex, which utilises the motor neurons of the peripheral nervous system to transmit impulses in the form of electrochemical signals from the spinal cord, across the neuromuscular junction, and to skeletal muscle fibres to innervate them [12]. A motor neuron and the muscle fibres it innervates are together termed a "motor unit", which when stimulated results in forces being produced by the skeletal muscles which act through the various lever systems of the MSKS to produce bodily motion [12]. The use of the *lower-body* to produce purposeful and effective motion is an essential component of sports performance, where in common sports tasks such as walking, running, and jumping, as a few examples, the forces produced in the MUs of the lower-body NMS are transmitted to the ground via the MSKS resulting in ground reaction forces (GRFs) which produce a movement of the body into space [12, 111].

According to Newton's 2nd Law of Motion;

"*The rate of change in the momentum of a body is equal both in magnitude and direction to the force imposed on it.*"

Where the mass of a body is constant;

$$\text{“}f=ma\text{”}$$

[15, 112].

Where f = force, m = mass, and a = acceleration, the acceleration of a given mass will be directly proportional to the force produced, with higher and more rapid force production capabilities relative to body mass yielding greater acceleration [15, 112, 113]. Therefore, the ability to produce high forces (i.e., neuromuscular strength), express forces over a short period of time (e.g., RFD, reactive strength, time constrained impulse, etc.), with the aim to optimise GRF production within the GCT constraints of sports, are essential components of physical preparedness of the NMS in elite sports performance [15, 112, 113]. The collection of metrics which objectify these physical characteristics (e.g., via force plate testing) can be used as Key Performance Indicators (KPIs) for objective benchmarking [114, 115] and monitoring neuromuscular fatigue [65, 116].

A neuromuscular mechanism which is beneficial to the force generating process is the stretch-reflex, which is an automatic response to stimuli that does not require conscious control [117]. Muscle spindles are the specialised sensory receptors that are responsible for this process [118]. They are composed of intrafusal muscle fibres, which are innervated by sensory neurons, and are located alongside extrafusal muscle fibres (i.e., the contractile element) within skeletal muscle [12]. Muscle spindles provide feedback regarding the length and rate of change of muscle fibres, which helps to prevent muscular injury and acutely enhance force production [118]. When skeletal muscle is lengthened, both the contractile elements and the muscles spindles are stretched [12]. Then, the sensory neurons are activated, this information is transmitted to the spinal cord, and the neurons synapse with motor neurons which are transmitted back to innervate the extrafusal muscle fibres within the same muscle [12]. This process typically occurs in the sequence of a rapid eccentric muscle action followed by an immediate rapid concentric muscle action, and the concentric action receives an enhancement in force generating potential [118]. This process is referred to as the "SSC" and plays a significant role in optimal physical preparedness of the NMS, particularly in sports [118]. A practical example of this process is best described in a CMJ because it consists of a braking followed immediately by a propulsive component [25], and thus benefits from the stretch reflex and the storage and release of elastic energy in the tendons [118]. The CMJ typically results in a greater JH than the SJ, for example, where the SJ only consists of a propulsive component, and thus the SSC is not activated in this task [118]. However, it is important to note that the differences in JH between these tasks has also been considered a result of the countermovement motion allowing the build-up of a high level of force before the start of propulsion (i.e., force at zero velocity), proposed as because of an increased active state via fraction of attached cross-bridges, resulting in subjects producing more work over the first part of propulsion [119].

3.5 Neuromuscular Fatigue

As described previously, the degree to which each individual athlete's NMS responds (i.e., internal response) to a physical training stimuli (i.e., external workload) is idiosyncratic [19]. Additionally, high-intensity external workload also differs between competing athletes, therefore, levels of neuromuscular fatigue and preparedness will differ between soccer athletes following training and competitive matches [120]. Because physical adaptations in response to exercise occur only during rest, improper recovery may result in residual fatigue [107] and consequently an athlete might not reach the supercompensation phase [77, 78]. This leads to an increased risk of non-functional over-reaching, overtraining, soft-tissue injury, and sub-optimal physical development. Therefore, identifying the degree of reduction in NMF (i.e., as a result of fatigue) an athlete has incurred would help practitioners prescribe the correct strategies and time periods to optimise recovery. Neuromuscular fatigue is defined as a reduction in maximal force-generating capacity of the NMS [121]. What makes the determination of neuromuscular fatigue more complex is that it consists of a combination of both neural and contractile impairment [72, 74], where it may result from central (neural) processes controlling the discharge rate of motoneurons, or peripheral (contractile) processes distal to the neuromuscular junction [121]. As such, some aspects of neuromuscular fatigue include central fatigue [122], neuromuscular junction inhibition [123], peripheral fatigue [124], and metabolic stress [104].

3.5.1 Central Fatigue

Central fatigue refers to neural processes which originate from the central nervous system (CNS) prior to the arrival at the neuromuscular junction [121]. Central fatigue manifests through a reduction in the efficiency of the CNS to provide neurotransmitters to and across the neuromuscular junction (i.e., a reduction in neural drive) [107]. It is a complex phenomenon where several factors contribute, and the information on the topic is less actionable than that related to peripheral fatigue [107]. This is potentially owing to the complexity of its determination, where expensive, complicated, laboratory-based equipment (e.g., magnetic resonance imaging) has been utilised in research investigating this phenomenon [107], where practical and commercially available solutions (e.g., force plates) would not suffice as a direct measurement but can give an indication of the total reduction in NMF to which central fatigue contributes. Central fatigue is thought to manifest primarily due to changes in the balance of inhibitory and excitatory neurotransmitters in the CNS [122]. A balance favoured to inhibitory neurotransmitters (e.g., serotonin) would result in a prevention of action potential, resulting in an inhibited ability for the NMS to produce force [122]. Oppositely, a balance favoured to excitatory neurotransmitters (e.g., glutamate) would enhance the potential to activate receptors on the postsynaptic membrane, and enhance the effects of the action potential, resulting in an enhanced ability for the NMS to produce force [122]. The modulation of neurotransmitters and thus central motor drive during exercise is thought to be partly caused by nociceptive afferent input, which impairs motor function to prevent the further development of fatigue [125]. Nociceptors provide feedback to the CNS regarding the state of the mechanical and metabolic (peripheral) fatigue, by stimulation of group III and IV muscle afferents, respectively [126]. Thus, central fatigue is an acute form of fatigue which characterised as creating a failure or unwillingness of the CNS to 'drive' motoneurons [125]. Despite previous difficulties in determining the contribution of central fatigue to overall neuromuscular fatigue, more recent research has investigated this by means of heart rate variability (HRV) analysis, which indirectly indicates a pronounced activation of the autonomic nervous system [107].

3.5.2 Neuromuscular Junction Inhibition

The neuromuscular junction is the point where the electrical signal is transferred. The neurotransmitter Acetylcholine (ACh) is released from the motor neuron and binds to the receptors on the muscle fibre, leading to depolarization and contraction of the muscle [12]. Neuromuscular fatigue can also be caused by neuromuscular junction inhibition, which would manifest through a reduction in the efficiency to deliver neurotransmitters to the skeletal muscles. Accordingly, neuromuscular junction inhibition is broadly described as an impairment in the communication between the nerves and skeletal muscle [123]. Because of this, it is not clear whether it should be considered a type of central or peripheral fatigue. It has also been termed Neuromuscular Transmission Failure (NTF), but regardless of the definition, an impairment of the function of the neuromuscular junction leads to a neuromuscular impairment [123]. There are three main components of the neuromuscular junction, which include the presynaptic terminal of the motor neuron, the synaptic cleft, and the postsynaptic membrane of the muscle fibres [123]. The process of skeletal muscle contraction is initiated through the arrival of an action potential at the presynaptic terminal, which contains synaptic vesicles filled with the neurotransmitter ACh [12]. This triggers the release of ACh into the synaptic cleft, which is a narrow gap between the presynaptic and postsynaptic membranes filled with extracellular fluid containing molecules that help to regulate the transmission and diffusion of these motor signals across to the postsynaptic membrane [12]. The postsynaptic membrane contains clusters of ACh receptors, which bind to ACh, leading to the opening of ion channels and the depolarization of the muscle fibre [12]. This depolarization spreads along the length of the muscle fibre, which leads to the release of calcium ions from the sarcoplasmic reticulum, and the subsequent contraction of the muscle [12]. Consequently, fatigue of the neuromuscular junction is regulated by a variety of factors, including the concentration of ACh in the synaptic cleft, the activity of various enzymes and proteins involved in the regulation of neurotransmitter release the number, synaptic plasticity, and the density and function of ACh receptors on the postsynaptic membrane [123]. However, the authors of previous research have proclaimed that an impairment of the neuromuscular junction through a depletion of ACh in the motor end plate is unlikely to be a primary mediator of neuromuscular fatigue, because neuronal impulses are not blocked whilst fatigued at the neuromuscular junction structure, and ACh is not fully depleted [107]. Rather, it is considered that neuromuscular fatigue during exercise is regulated via higher structures in the CNS (i.e., central) and feedback signals from the muscle (i.e., peripheral) [107].

3.5.3 Peripheral Fatigue

Peripheral fatigue refers to contractile processes which are distal to the neuromuscular junction [121]. Peripheral fatigue is thought to be a consequence of both mechanical (i.e., impairment of the contractile mechanisms) and metabolic stress [79], which manifest and interact in different degrees dependent on the physical stimuli [107]. Mechanical fatigue typically refers to the accumulation of microtrauma, increased serum creatine kinase (CK) activity, and the development of muscle damage [107]. Previous research has reported an association between serum CK level and impaired force generating capacity following exercise [127]. Metabolic stress occurs when the metabolic demands of muscle contraction exceed the capacity of the aerobic and anaerobic energy systems to produce ATP [99]. Typically, it is considered to be a combination of substrate (e.g. phosphocreatine and glycogen) depletion and the accumulation metabolic by-products [107], such as H^+, inorganic phosphate, and ADP [104], which can impair muscle contractility [2, 5], and cause acidosis (i.e., lowering of blood pH) [105]. Although phosphocreatine is re-phosphorylated from its component parts of creatine and inorganic phosphate quickly (half-life of ~22 seconds) during periods of low intensity activity, the accumulation of ADP (i.e., the depletion of ATP) leads to a detriment to ATP-dependent processes such as fibre contraction, ion pumping, and protein synthesis, an increase in H^+

reduces the sensitivity of the calcium ion channels in the muscle cells, and an impairment in muscle fibres' ability to contract [104].

Peripheral fatigue is determined by exercise type, intensity, duration, and recovery duration. It can also be systemic or localized to specific muscle groups. As a practical example, performing repeated bouts of the same activity, through the same Range of Motion (ROM; e.g., cycling), at maximal exertion, and with minimal rest, will cause a significant build-up of metabolites (i.e., metabolic stress), leading to an acute reduced ability to coordinate the working muscles in that particular fashion [72, 74, 79]. However, there is potential to continue alternative physical activity via dynamic activities (e.g., running, jumping, or upper-body activity), which utilise a combination of different muscle groups, and thus allow the body to "compensate" for this localised metabolic stress. Additionally, if these activities do not overload all MUs with a high amount of mechanical tension, mechanical stress (e.g., muscle damage) may not be substantial, meaning NMF may mostly replenish once the localised metabolic stress has subsided [72, 74, 79]. Alternatively, if an activity involving multiple muscle groups, performed in bouts of maximal exertion, but with sufficient rest in-between (e.g., during maximal strength focused resistance training) is performed, this would allow time to recover metabolically to the point that metabolic by-products are not a limiting factor to performance, and the same activity could be repeated until sufficient muscle damage was accumulated, or energy substrates were depleted. Where metabolic stress would result in a neuromuscular impairment acutely, muscle damage can manifest acutely (i.e., as in the example provided above) or chronically if micro-trauma is achieved over multiple sessions without sufficient recovery between sessions. Like with central fatigue, expensive and complicated (and invasive) laboratory-based equipment are typically utilised to determine metabolic stress and muscle damage (e.g., blood samples taken for a lactate threshold [128] or CK test [127], respectively) directly, where practical and commercially available solutions (e.g., force plates) would not suffice as a direct measurement but give an indication of a total reduction in NMF due to both central and peripheral fatigue.

3.6 Evaluating Neuromuscular Function

As discussed, it is critical for physical coaches to generate a *physical profile* (i.e., needs analysis) for an athlete by understanding the abovementioned key mechanisms of NMF, and an appreciation for the short and long-term effects of training and match play in any sport. Next, the process of practice for the physical coach (Figure 1.2) demonstrates a large emphasis placed on *evaluation procedures*, which is essential to enable a physical coach to monitor changes in neuromuscular fitness and make informed decisions on training direction to optimise physical preparedness [19]. Warren et al. [129] suggests that objective measures provide the most effective means of evaluating the magnitude and time course of changes in NMF resulting from physical activity. This allows for the appropriate planning of recovery back to and beyond baseline, ensuring physical preparedness is optimised for when it is required most (i.e., for competitive matches). Accordingly, there is a large and growing emphasis within sports science literature on innovative strategies to evaluate changes in physical preparedness, with a plethora of physiological, biochemical, psychological, and biomechanical performance markers available that help to inform coaching staff about an athlete's state of fitness, fatigue, and projected recovery [23, 110, 130]. Lower-body NMF has been objectively evaluated in a variety of ways in scientific literature, and for differing reasons, so information of best practice on this topic would help practitioners achieve optimal outcomes in their roles. Comfort et al., [30] described some key considerations for testing selection, which included;

(1) The relationship between the performance in specific test metrics and sports actions (e.g., sprint speed) [30],
    a. Firstly, choosing performance indicators should be context-specific, accurately reflecting the important characteristics of the athlete and KPIs of the sport, thus making them "meaningful" (e.g., which metrics most relate most to physical performance?) [31-35].
(2) The validity and reliability of specific tests and metrics [30],
    a. Secondly, tests must be valid and reliable [36]; validity refers to the degree to which a test or test item measures what it is supposed to measure and is one of the most important characteristics of testing, and reliability is a measure of the degree of consistency or repeatability of a test (i.e., information needs to be accurate, repeatable, and thus sensitive enough to detect changes in NMF) [36].
    b. For a test to be valid it must be reliable, because highly variable results have little meaning [36]. However, a reliable test may not always be valid, because although the results are consistent over time, the test may not measure what it is supposed to measure [36].
(3) The availability of normative data and benchmarks for specific tests [30],
    a. Test metrics hold utility for objective benchmarking only if they discriminate between comparable groups (e.g., playing levels and/or age groups), and mass datasets facilitate a comparison of athlete data to established norms.
(4) The feasibility of test application relative to the available facilities and equipment [30],

a. Finally, in elite sports settings, additional considerations specific to test selection are time-efficiency (i.e., how quick and easy can the test be performed?) and physical demand (there is a requirement for a test to be relatively non-fatiguing in nature) [23].

Section 3.7 Evaluation Procedures will discuss neuromuscular testing with consideration for these four key points.

3.7 Evaluation Procedures

3.7.1 Single-joint Evaluation Methods

Isolated evaluation methods are an example that have been used in scientific literature to determine NMF [129]. Isokinetic dynamometers have been used to determine isometric strength through assessing joint torque at different static joint angles and to determine torque-angular velocity relationships in different movement actions (i.e., eccentric, isometric, or concentric) at different angular velocities [131, 132]. Electromyography (EMG) has also been applied in such studies to determine muscle activation during such tests as a proxy to determine the effects of exercise-induced fatigue on NMF [133, 134]. Such methods are typically employed to monitor the recovery of NMF in specific muscle groups back to baseline following injury [135, 136]. An isometric assessment would require one to perform a Maximal Voluntary Contraction (MVC) of a muscle group at a fixed joint angle for 1–5 seconds to determine neuromuscular strength, RFD, and joint angle-torque, as a few examples [137, 138]. Isometric strength has appeared to be reduced immediately post-exercise, and recovery identified as gradual and prolonged, using these assessments [131, 139]. The magnitude and time course of strength loss has appeared dependent on the training history of the muscle group, with the greater and longer lasting strength loss observed in more relatively inactive muscle groups (e.g., elbow flexors) [140, 141] versus the more active and capable locomotory muscles of the lower limbs [102, 142].

Immediately following an 85 km cross-country ski race [143], a 42.2 km marathon [144], and a 65 km ultramarathon race [145], reductions in isometric knee extensor strength of 10%, 26% and 30%, respectively, have been reported. Following marathon running, Avela et al. [146] reported a 30% reduction in ankle extensor strength and RFD, with full recovery to baseline by 2 and 4 days post-race, respectively [143-145]. With regards to resistance training, early work by Komi and Viitasalo [102] demonstrated a 35% reduction in knee extensor strength and a decreased RFD which did not begin to recover until +2 days post resistance training consisting of 40 maximal eccentric actions performed on a leg press apparatus. Recent work by Byrne and Eston [147] demonstrated a 30 to 40% reduction in knee extensor strength with recovery incomplete (approximate return to 95% of baseline measures) +7 days post resistance training consisting of 100 repetitions of the eccentric phase of the barbell squat exercise, performed with a load of 80% of concentric one repetition maximum [148].

Based on these investigations, isometric single-joint evaluation methods seem to hold utility for identifying neuromuscular fatigue in a variety of populations, following various physical stimuli. However, a drawback to such examinations is that relative strength loss is not uniform across joint angles, where several investigations have revealed a disproportionate loss of strength at joint angles when comparing short versus optimal versus long muscle lengths [147, 149-151]. Following eccentric exercise specifically, a shift in the length-tension relationship towards longer muscle lengths for maximal force and torque generation has been shown to occur in particular [152]. An explanation proposed for these findings is that a longer muscle length is required to achieve the same myofilament overlap and hence force production after eccentric exercise due to an increase in series compliance as a result of overextended sarcomeres [153]. These findings suggest that strength loss will be exacerbated when muscle groups are activated at shortened lengths after eccentric exercise (i.e., when the knee extensors are activated, and the knee joint is close to full extension). Additionally, whether the shift in optimal angle is present for a period as long as the observed reduction in strength [151], or whether it recovers whilst the reduction in strength remains, is yet to be identified [150, 152]. These points highlight a major concern with the standardisation procedures regarding the chosen joint angle of isometric single-joint evaluations of NMF.

Several researchers have also used isokinetic dynamometry to investigate whether strength loss after physical activity is dependent on the muscle action being performed (i.e., eccentric, isometric, or concentric) [154-156]. Interestingly, when neuromuscular strength at a single angular velocity of movement is compared between muscle actions there appears to be no significant or meaningful differences in the magnitude of strength loss or the rate of recovery [154-156]. But, when investigating whether strength loss and rate of recovery are dependent on the angular velocity of movement, interesting results have emerged with several authors reporting strength at higher angular velocities of movement to be affected to a lesser extent than slower angular velocities of movement and isometrically [154-156]. Isokinetic dynamometers are also compromised in their ability to replicate the sports specific movement velocities of multi-joint movements, being limited to angular velocities up to approximately 7 rad/sec, whereas multi-joint dynamic movement velocities can be approximately 17 rad/sec for knee flexion during sprinting, for example [157]. Therefore, whether used concentrically, isometrically, or eccentrically, single-joint assessment methods seem to present a dilemma regarding the standardisation of joint angle and angular velocity, which raises uncertainty around their utility (e.g., accuracy, reliability, and sensitivity) to detect changes in NMF.

Additionally, the utility of these techniques is limited when we wish to extrapolate to the sporting context as they do not give a systemic and dynamic representation of lower body NMF and could be regarded as not sports specific [158]. Single (i.e., not coupled) forms of eccentric muscle action rarely occur in isolation in natural human movement, which rather occurs typically in a sequence of an eccentric action followed by a concentric action (SSC action) [158]. As a broad example, training that induces a high volume and intensity of short-accelerations, decelerations, and changes in direction in small spaces (e.g., a small-sided game [SSG] in soccer) will occur through SSC actions with a greater demand on the quadriceps group, in particular, in comparison to the hamstrings due to the nature of the stimulus [159]. Due to this, determining acute changes in lower-body NMF following the activity using a single-joint assessment of the hamstrings muscle group would seem illogical to determine the effects of this specific activity, because it would be overlooking the primary area of focus (i.e., the quadriceps), which would be a major concern if using the results to inform the training process. Even if hypothetically the quadriceps muscle group were focused on in this example, this may still give an unfair representation of lower-body NMF holistically, because during dynamic activity an athlete can compensate by recruiting different muscle groups to a greater extent and thus utilising different movement patterns, therefore, despite a reduction in NMF of the isolated muscle group, overall physical preparedness may not be as impeded as the results of the single-joint assessment in the example would suggest [158].

Over and above all these points, the utilisation of single-joint assessment methods is practically unfeasible from a “physical performance” perspective in team-sports, where a physical practitioner may be afforded a maximum of 2 hours to collect a range of KPIs from various tests with ~20 athletes. Although gaining a holistic view using an evaluation of each individual muscle group would be possible, the time it would take to evaluate this across a whole squad is impractical for the daily consumer. To conclude, although single-joint assessment methods may hold utility in injury rehabilitation settings [135, 136], the combination of points addressed here highlight why more systemic and dynamic evaluation approaches are a more contemporary practice for the determination of physical preparedness [160, 161].

3.7.2 Multi-joint Evaluation Methods

Elite level practice can be enhanced with the use of hardware which permits the collection of dynamic and isometric multi-joint evaluation data within routine morning medical screening to monitor recovery, gym-based sessions to increase training intent, and pitch- or track-side after training to monitor fatigue [162]. Additionally, software which provides immediate feedback is important for accurately and quickly informing players, coaches, and medical staff on individual preparedness to train and recommended training prescription [162]. For example, force plates are among the most commonly used biomechanical apparatus in the field of S&C, reportedly used by 50% (N = 26 out of 52) and 30% (N = 10 out of 33) of surveyed S&C coaches working in professional soccer [161] and professional cricket [160], respectively. Some limitations of recent developments in force plate technology include that they are wired systems (meaning that they require an electrical supply which restricts testing locations) and either do not come with test analysis software, the included software does not automate calculations or, in some cases, does not include recommended calculations for a broad range of tests limiting the utility of the resulting data.

To tackle these issues, the world's first wireless dual force plate system was recently developed (circa 2016) by HD Inc. (Westbrook, Maine, USA) and has since been purchased by many physical practitioners who work with athletes around the world. As well as producing robust, valid, and fully portable force plates, HD Inc. have also developed proprietary software which automatically calculates a range of variables across several tests and reports data immediately after the test has been conducted. This proprietary software produces force-time curves, and with the integration of forward dynamics processes in VJ tasks, a multitude of KPIs relating to acceleration, velocity, and displacement of the COM can be discerned [162]. Thus, athletes can be tested using robust procedures within a few minutes and coaches can gain immediate access to informative data on their athletes.

The rise in use of force plates in professional sports is likely due to the development and release of such affordable and commercially available portable force plate hardware which is validated against industry gold standard systems [57, 114, 163], alongside this proprietary software which produces quick and informative reports [160, 161]. These force plate systems can be considered to provide accuracy, robustness, practicality, and feasibility [25, 111], thus facilitating the best opportunity to gain informative data on NMF in practical settings. These factors are important to consider given that the monitoring of NMF and determining changes in physical preparedness is a task specific to, and historically a luxury only available to, elite sports organisations. Accordingly, it also makes sense that most literature related to evaluating NMF using force plates is performed with populations defined as elite or professional athletes [164], with fewer investigations in collegiate, university, and youth athletes [23].

Because of such technological advancements, the HD Inc. hardware and software has the potential to revolutionise the way in which force plate assessments are conducted globally. There is a new opportunity to gain more informative data on physical preparedness and NMF in environments where less practically feasible systems have been limited previously [111, 162]. Despite force plates becoming more commonplace in professional sports environments, with many S&C coaches testing their athletes daily [22], how to best utilise force plates in practice to monitor NMF and inform decision making is yet to be realised. There is a lack of research on how best to integrate this technology with multiple force plate tests (e.g., dynamic assessments and isometric assessments), conducted with appropriate methods, to provide a comprehensive evaluation and monitoring of athletes' lower body NMF. Rigorous research is required to evaluate and develop sport-specific force plate testing batteries for monitoring lower body NMF. This would contribute to knowledge on this topic and the promotion of best practice via research and provide research-informed force plate testing batteries for monitoring acute changes in athletes' lower body NMF to be embedded into the HD Inc. force plate software, and subsequently applied by practitioners globally. Force plates are most commonly utilised for multi-joint evaluations of lower-body NMF [160, 161]. However, as discussed, there are a plethora of methods, tests, and metrics available to practitioners who seek to use force plates to evaluate and monitor NMF in sport. Some approaches may be more or less appropriate than others dependent on the population and desired information [31-34], which poses the problem of rationalising which tests and resulting metrics are most appropriate to use [31-34].

3.7.2.1 Vertical Jump Assessments

A comprehensive overview of *dynamic* lower-body NMF has been achieved in sports science research with detailed analyses of VJ tasks. Following detailed analyses of force-time curves, authors have presented key information of the validity [21, 57], reliability [58-61], meaningfulness (relation to sports specific actions) [32, 62-64], and discriminatory capabilities (i.e., for objective benchmarking) [27, 37-39] of specific metric types such as outcome, strategy, kinetic, and ratio measures across a range of VJ tests. Such research has allowed inferences to be drawn on the potential of specific tests and measures to be utilised as a proxy for informing an athlete's current state of NMF and physical preparedness to inform training prescription. The CMJ test is the most popular test prescribed to assess neuromuscular fitness and fatigue (preparedness) developments following physical training in the football codes [23]. The interest in this test is due to it utilising the SSC which makes it relevant in the evaluating lower-body reactive strength qualities, and it requires minimal familiarisation, is quick to perform, and is relatively non-fatiguing, meaning a variety of metrics have demonstrated consistently good between-trial reliability (CV ≤ 10%), and thus make for feasible metrics for monitoring changes in NMF [65-67]. When applying the CMJ test, reactive strength capabilities have been primarily evaluated using the Modified Reactive Strength Index (mRSI) metric [65, 67, 162, 165]. mRSI provides an overview of SSC function and NMF in the CMJ test where there is no identifiable GCT [67]. To calculate mRSI, JH is divided by time to take off (the time between the initiation of the countermovement motion and the point of take-off), essentially creating a time-relative outcome measure. McMahon et al. [27] reported that mRSI discriminates professional and youth rugby league athletes, and Bishop et al. [115] proposed that mRSI may theoretically be considered appropriate for detecting neuromuscular fatigue induced by intense physical activity because it is calculated very similar to the FT:CT, which has been suggested as a reliable indirect indicator of NMF using CMJ testing [65-67], and both these metrics have previously demonstrated almost identical within-session reliability [59].

From an objective (fitness) benchmarking perspective, a greater mRSI would indicate better reactive strength characteristics within a group of athletes, owing to greater braking and propulsion force, impulse, velocity, and power production, as seen in previous research [67, 166]. From a neuromuscular (fatigue) monitoring perspective, (e.g., on a weekly or daily basis), relative to baseline, it might be used as a proxy to determine neuromuscular fatigue, where a value less than baseline (i.e., within the identified measurement error) would indirectly indicate neuromuscular fatigue following training [67, 166]. However, when utilising ratio metrics (e.g., mRSI) for either purpose, it is also essential to consider the constituent parts of outcome (e.g., JH) and strategy (e.g., time to take-off) independently, so that a change in the ratio measure can be contextualised. This is particularly important also given that it has been reported in previous research that strategy metrics are affected by neuromuscular fatigue. For example, Gathercole et al. [116] reported that CMJ time to take-off largely (ES = 1.90) increased from 0.77 ± 0.09 s to 0.83 ± 0.11 s following a lower-body fatiguing repeated stair climb exercise protocol with national level snowboard-cross athletes. Future investigations into the utility of specific CMJ variables by their ability to detect acute changes in NMF (i.e., their test-retest reliability) and ability to be utilised as objective benchmarks (i.e., their discriminatory capabilities of competitive levels and age groups) may prove useful to practitioners. Such examinations could be completed on a cohort-specific basis in several sports where this information is lacking (e.g., in senior and youth soccer players).

The CMJ is a task that is considered "ballistic", and not "plyometric". This is because a plyometric task has an identifiable GCT of <250 ms, where it is not uncommon for the time to take off of a CMJ test to exceed 700 ms in recreational subjects [21] and professional athletes [27]. Consequently, mRSI is more a representation of slow SSC capacity [67]. A measure which is related to fast SSC capacity is the Reactive Strength Index (RSI), which is typically calculated by dividing JH by GCT, and thus only applies to plyometric tasks which utilised the SSC and have an identifiable GCT of <250 ms (when executed correctly) [67]. The most popular example is the drop jump (DJ) test [23], which has been utilised in various research articles relating to validity [21] and reliability [167] of VJ measures. Despite their similarities as proposed measures of reactive strength capability, McMahon et al. [67] proposed that mRSI and RSI cannot be utilised interchangeably, because the tasks utilised to calculate these measures (i.e., the CMJ and DJ) differ both kinetically and kinematically. In a situation where the monitoring of slow SSC capacity is of interest, CMJ-derived mRSI would be more appropriate [67]. Likewise, if fast SSC capacity is of interest, then DJ-derived RSI would be more appropriate [67].

The correct execution of the DJ test is paramount to its repeatability. The test requires a level of neuromuscular capacity and familiarity to demonstrate technical competency, and thus reliable results. For example, utilising a portable force plate system, twenty recreationally active adults performed the DJ and CMJ tests with a peak braking force of 4076.00 ± 1106.00 N and 1952.70 ± 320.31 N, respectively [21]. If an athlete does not possess the neuromuscular capacity and familiarisation required to perform the DJ test correctly, the braking forces imposed on the lower body on landing would likely be too great to decelerate their COM quickly, and the test would likely be performed with a more compliant strategy and longer GCTs than required. Such a technique would more resemble what is known as a depth jump, and if performed in this way, would negate the DJ's ability to assess fast SSC capacity [67, 168]. Another proposed limitation to the DJ assessment is that previous research has reported differences between effective box height and actual fall height [169], where Geraldo et al. [170] observed a progressively increasing difference (an average of 2 cm increase in difference per 10 cm increment in effective box height) between effective box height and fall height at effective box heights of 20, 30, 40, and 50 cm.

A difference in fall height would change the touchdown velocity and thus the force–time characteristics of the braking phase (e.g., a change in net braking impulse), and, if using the DJ as a task during training, it may affect the accuracy of the prescription of DJ Training Load (TL). Additionally, because the mechanical loading is higher than that of the CMJ, it seems logical to suggest that this test might be perceived negatively by coaches and athletes who aim to minimise additional fatigue and susceptibility to injury in the monitoring process. The DJ test also requires additional equipment (i.e., a box to drop from) to perform the test, and authors of previous research have identified discrepancies in standardised drop height vs actual fall height in the DJ test [21, 171], which would lead to erroneous measures of NMF [67, 168], making data less comparable between athletes, groups, and sessions, and ultimately reducing the DJ test's viability to benchmark and monitor changes in NMF. These points may explain why, contrary to the findings regarding CMJ-derived mRSI, research has identified a high degree of between trial variability (CV > 10%) in DJ-derived RSI, which would render the measure less able to detect acute fatigue-induced changes in NMF [67, 168]. Given that reliability is cohort specific, a comparison of the reliability of CMJ- and DJ-derived measures requires further exploration with different populations [67, 172].

Alternative plyometric RJ assessments which are employed to assess fast SSC capacity [58, 173] include the 60 s rebound test [174], 10/5 RJ test [172], 5-max rebound test [61], and the CMRJ test [58, 173]. Despite their use in literature, there is a lack of consensus regarding which RJ metrics hold utility for objective benchmarking, due to lack of information regarding which metrics discriminate between competitive levels and age groups. However, there is growing interest in determining which RJ metrics can be used as a proxy to monitor neuromuscular fatigue, with more investigations being conducted investigating the reliability of metrics in a variety of populations [61, 172]. The 60 s rebound test has faced scrutiny due to its high volume per set, with perceived unnecessary repeated impact loading and potential fatigue in the musculature surrounding the ankle and knee joints, which could heighten the risk of injury, thus making it unfavourable [172, 174]. Similarly, the 10/5 RJ test requires an athlete to perform a preliminary CMJ and then perform ten consecutive repeated jumps (aiming for GCTs of under 250 ms) with the five jumps consisting of the highest JHs that meet the GCT criteria taken for subsequent analysis [61, 172]. The test has achieved good between-trial reliability (CV ≤ 10%) with negligible differences between the mean five best RSI and reliability values attained [61, 172].

Research by Stratford et al. [172] reported that 7 repetitions were required to achieve stability in the mean RSI across trials and 7 to 10 repetitions were needed to achieve peak RSI within a trial. If accepted, this could imply that RJ tests performed with less than 7 repetitions (e.g., the 5-max rebound test) hold less utility as more repetitions may be needed to produce peak output (i.e., RSI) to determine neuromuscular capacity [67]. However, these findings could be attributed to a learning effect over repetitions, the natural bio-variance of movement which means no two actions can be executed the same, or the adoption of a pacing strategy by the subjects as identified by the gradual decrease in GCTs and greater JHs displayed over continuous repetitions [172]. Additionally, investigating this in populations with greater physical capacity and familiarisation to RJ tests (e.g., professional athletes) might prove useful. It has also been suggested that only one trial of the 10/5 RJ test may be necessary to achieve acceptable reliability, which would prevent inducing unnecessary additional fatigue to athletes and be less time-consuming for practitioners [172]. Despite this statement, even a single 10/5 RJ trial requires twice as many repetitions for set than a 5-max rebound test, and tenfold more repetitions than a DJ test, which could be perceived negatively regarding mechanical loading, particularly if the test is being prescribed in the process of objectively assessing neuromuscular fatigue.

Despite the 5-max rebound test possessing lower volume per set, which may be favourable from a fatigue perspective, the 5-max rebound test has displayed contrasting consistency (CV%) in separate studies, where between-trial reliability in key ratio and strategy metrics (e.g., RSI and GCT, respectively) reported greater (11-21%) and lower (7-8%) reliability than is commonly deemed reliable enough (<10%) to detect worthwhile changes within a specific subject pool [61, 175]. The CMRJ consists of a preliminary CMJ followed by a single RJ, requires no additional equipment to conduct the test, and unlike the discrepancies seen between standardised box height and actual fall height in the DJ test [21], the RJ fall height (i.e., preliminary CMJ height) has demonstrated acceptable absolute and relative between-session reliability in youth soccer players [58]. Xu et al. [173, 176] also identified acceptable absolute (CV < 10%) and relative (Intraclass Correlation Coefficient [ICC] > 0.75) reliability in CMRJ metrics such as JH, countermovement depth, time to take-off, and GCT. In these studies, similarities were seen in hip, knee, and ankle joint work between the DJ and CMRJ tests, and the reliability of kinetic measures was similar, therefore, the authors offered the CMRJ as a potential alternative to the DJ test [173, 176].

In both these studies the authors reported GCTs of >300 ms for the DJ and CMRJ tests in both testing sessions, thus failing construct validity as an assessment of fast SSC capacity [173, 176]. This indicates an issue in data collection, for example, an incorrect demonstration, verbal cueing, correction through coaching, or a lack of physical capacity of the recruited subjects [173, 176]. The latter could be due to the demographic utilised in these studies, where Xu et al. [173, 176] recruited 33 sports science students with mixed sports backgrounds. Given this, it is possible that these subjects did not possess the physical capacity required to produce sufficient peak braking forces to perform the test correctly, however, this cannot be discerned given that kinetic measures (e.g., peak force and power) during any phase of the test were not reported [173, 176]. The authors stated themselves that the recruited subjects had minimal experience with plyometric tasks [173, 176], and suggested that for these reasons, these results may hold limited utility for informing the practice of professional athletes [176]. Theoretically it seems the CMRJ might be an alternative option of a fast SSC test which requires minimal repetitions (i.e., only a single RJ), requires no additional equipment (i.e., not box is required), and overcomes the fall height issues reported for the DJ. However, the ability for this test and its measures to be utilised in objective benchmarking (i.e., do the measures discriminate between age groups?) and monitoring acute changes in NMF (i.e., do the measures present acceptable test-retest reliability?) in professional soccer players is yet to be determined. Overall, the utilisation of RJ-derived force-time measures for the purpose of objective benchmarking and monitoring training-induced changes in NMF is yet to be seen in research. Stratford et al. [172] proposed the use of upper- and lower-bound Standard Error of Measurement (SEM) statistics to establish a bandwidth of 'normal' performance variance in 10/5 RJ metrics. Applying this to other RJ tests could help practitioners identify the minimal detectable difference required to see a change in specific RJ measures and propose recommendations on their utility to detect changes in NMF over time. Accordingly, research is warranted to further explore the use of RJ variations (e.g., 1, 3, 5, and 10 RJs), where comparing results to the widely studied DJ test might help to determine which RJ variations could alternatively accurately and reliably benchmark and monitor changes in NMF [172].

3.7.2.2 Metric Selection Considerations

Determining which VJ metrics are relevant as KPIs for athletes can be confusing given the vast range of metrics that are automatically analysed and immediately available via proprietary software [115]. As illustrated in the deterministic model by Hay & Reid (Figure 3.1) [177], which details the key contributors of VJ performance, because gravitational acceleration (g) is constant (9.81 m/s^2), TOV is the primary modulator of JH (Figure 3.1) [178-183]. Consequently, TOV and flight height (i.e., JH) have been of interest in the VJ assessment of NMF [66, 178-181]. However, a potential drawback to dynamic assessments of NMF (i.e., VJs) is that, although outcome measures are intuitive to athletes and coaches, the outcome of the task is directly influenced by the movement strategy (e.g., braking depth and movement time) employed during tasks [178-183], thus the outcome of a VJ can be altered via changes in strategy [184]. Because differences in VJ strategy are created via alterations in VJ force-time characteristics, a change in outcome may not necessarily reflect a positive development in kinetic output but an adoption of a different strategy entirely. Thus, despite their popularity [23], it would be unwise to utilise outcome measures alone, where it is potentially more important to understand what is "driving" the output when utilising force plate data to profile physical capacity and monitor changes in NMF over time as a proxy for determining neuromuscular fatigue.

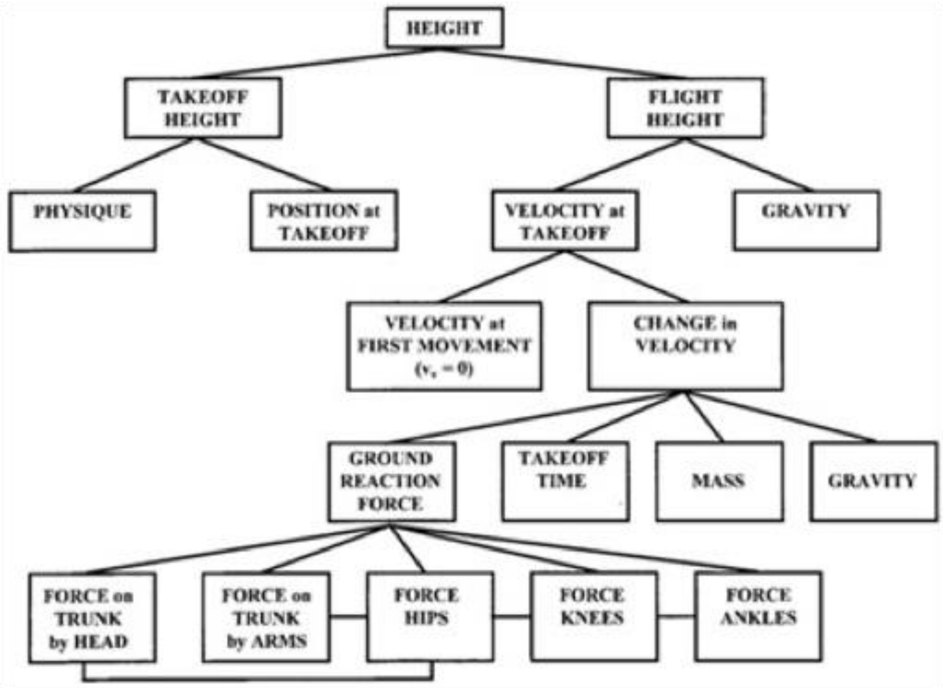

Figure 3.1. Deterministic Model of Vertical Jump Performance, by Hay & Reid [177].

Newton's second law, commonly referred to as the impulse-momentum theorem, states;

$$\text{“}F_{mean}\, \Delta t = mv - mv0\text{”}$$

[15, 181].

Where Fmean is mean force, Δt is the time of force application, m is mass, v is final velocity, and v0 is initial velocity, and therefore, impulse (Fmean Δt) equals change in momentum (mv – mv0). Research has indicated that the employed impulse production has been reported to alter VJ strategy and contribute to changes in the vertical displacement, and therefore, the TOV of the body's COM [179, 181, 183]. The latter can be determined by altering the abovementioned equation to calculate impulse relative to body mass;

$$\text{“}(F_{mean}\, \Delta t)/m = v - v0\text{”}$$

[15, 181].

Because velocity is zero at the initiation of the propulsion phase of VJs, initial velocity will always remain zero in this equation, and therefore impulse relative to body mass determines final velocity, or TOV. A greater generation of relative propulsive impulse would therefore produce a greater TOV to enhance flight height (i.e., JH). As an increase in net propulsive impulse can manifest via an increase in net propulsive force or time, it seems rational to consider that both the force-time characteristics produced, and the strategy employed to achieve the outcome should be monitored in VJ tasks.

Merrigan et al. [32] utilised the Random Forest Regression (RFR) analytical method to determine a small subset of force-time metrics which are most influential to the outcome (i.e., JH) of the CMJ test. A cross-sectional, retrospective, research design was employed with eighty-two Division I National Collegiate Athletic Association (NCAA) football players during the team's first week of their "off-season" [32]. In this athlete population, the RFR analysis indicated that greater JH was achieved by attaining a deeper, faster, and more forceful countermovement [32]. Consequently, the authors proposed that the following metrics might be most relevant for monitoring changes in NMF utilising the CMJ test, as they relate most to JH; braking and propulsion time, absolute and relative mean and peak propulsion force, absolute and relative mean and peak propulsion power, countermovement depth, and braking-to-propulsion mean force ratio [32]. Recommendations were also presented in a review by Bishop et al. [115] for the utilisation of kinetic measures such as propulsive peak power, mean force, and impulse for "performance profiling". Utilising a variety of metric types during different phases of VJs (e.g., the unweighting, braking, propulsion, flight, and landing phases), rather than only assessing outcome measures such as JH alone, may provide a better representation of an athlete's physical capacity, and changes in NMF over time [27, 28, 67, 113, 118, 162, 178, 185].

For practitioners with limited time, staffing, and facilities, a streamlined approach of selecting metrics which hold utility for both objective benchmarking and monitoring acute changes in NMF as a proxy for determining neuromuscular fatigue is essential. The CMJ test has been suggested a useful tool which is easy to apply for both purposes (i.e., monitoring acute fatigue- and chronic training-induced changes in NMF) [116]. For example, Gathercole et al. [116] reported large to very large (ES = 1.60 to 3.09) reductions in CMJ strategy metrics (i.e., braking time, propulsion time, and time to take-off) with a small (ES = 0.42) increase in JH following a 19-week training programme, consisting of a mixture of resistance and technical training. Gathercole et al. [116] also reported small to large (ES = 0.88 to 1.91) increases in CMJ strategy metrics (i.e., braking time, propulsion time, and time to take-off) immediately (+30 min) following a lower-body fatiguing repeated stair climb exercise protocol with national level snowboard-cross athletes [116]. Increases in CMJ strategy metrics can result in a maintenance of net propulsive impulse and thus the outcome (i.e., TOV and JH) of a CMJ task, even with a decrease in mean force [15, 181]. Accordingly, Bishop et al. [186] suggested that a combination of categories such as ratio (e.g., RSI, mRSI), outcome (e.g., JH), and strategy (e.g., GCT, time-to take-off, countermovement depth) metrics might be of interest when profiling and monitoring athletes. The study by Gathercole et al. [116] did not include other VJ tests or ratio metrics, therefore, further assessment is required to determine the dual-purposed applicability of VJ metric types (e.g., outcome, strategy, kinetic, and ratio) for producing objective benchmarks and monitoring acute changes in NMF in other professional sports populations.

3.7.2.3 Isometric Assessments

Isometric assessments can avoid potential within-subject differences in strategy with a standardised set-up [187]. The most popular isometric assessment is the IMTP test, which is employed to give an indicator of lower body "strength" [188-190]. It is considered safer, less fatiguing, quicker to perform, and more practically feasible than dynamic repetition maximum testing (e.g., back squat) [187], particularly when evaluating large groups simultaneously (i.e., as generally seen in soccer). The IMTP test has been administered across a range of professional sports populations (including youth) to provide a direct insight into maximal and rapid force production capacity [191-196]. From a physical profiling perspective, the information valued from the IMTP test typically consists of measures related to absolute and relative maximal force production, RFD, and the degree to which an athlete can express their maximal force capacity in dynamic tasks (e.g., the CMJ test) via the Dynamic Strength Index (DSI) [188-190, 197]. Peak force derived from the IMTP has been related to the performance of various other physical tests, such as CMJ height ($r = 0.82$ [198]), SJ height ($r = 0.87$ [198]), 5 and 20 metre sprint speed ($r = -0.57$ and -0.69, respectively [199]), and COD speed in the T-Test ($r = -0.85$ [200]), 505 test ($r = -0.79$ [200]), and modified 505 test ($r = -0.57$ [199]), as a few examples. Additionally, it has been proposed in previous research that practitioners should be confident in assessing IMTP force-time characteristics of youth soccer athletes due to findings of acceptable absolute and relative reliability within- and between-sessions in male youth soccer players for various kinetic measures such as peak force, and force at various time-points (e.g., 30, 50, 90, 100, 150, 200, and 250 ms) [189]. As is the case for VJ tests, further assessment is required to determine the applicability of IMTP metrics for producing objective benchmarks and monitoring acute changes in NMF in professional and youth soccer populations.

3.8 Reporting and Reviewing Procedures

The process of practice for the physical coach (Figure 1.2) demonstrates an emphasis placed on utilising data to inform *training direction*. In fact, the primary purpose of evaluating soccer athletes' physical capacity is talent ID and goal setting for training [11]. To achieve this, once data has been collected, the next step is typically one of the following [41]:

(1) Analysis of an individual's or group's data to identify changes in performance over a specific training period (e.g., days, weeks, months, or years).
(2) Comparison of an athlete's scores to others within the group(s) they're included.
(3) Analysis of an individual's or group's performance relative to that of similar individuals (e.g., players in the same position) or groups (e.g., previous squads) tested in the past.
(4) Comparison of individual scores to local, state, national, or international norms (i.e., objective benchmarking).

Regarding point (4), objective benchmarks (i.e., goal setting) cannot be prescribed for key tests and metrics without the existence of cohort-specific normative data sets [114]. This is particularly important for youth soccer athletes in England who aspire to reach the professional level, as they progress through the Elite Player Performance Plan (EPPP) consisting of the Foundation Phase (FDP; U9 to U11), Youth Development Phase (YDP; U12 to U16), and Professional Development Phase (PDP; U17 to U23) phases [201]. Within the EFL academies typically structure the PDP to include a full-time "Youth Team" (YT; U17 to U18) scholarship programme where players will be evaluated over the course of 2 seasons for the potential to be offered professional contracts. During this process, player performance in all aspects of the Four Corner Model is considered. Because it is advised that published normative data and benchmarks should only be used within comparable groups [30], it seems rational to consider that normative data and benchmarks of professional and youth soccer players across a range of force plates tests of NMF specific to each competitive league in England (e.g., the EPL, EFL Championship, EFL League 1, EFL League 2, etc.) would be useful. This information would help physical coaches ensure their players are up to the physical standards of the league they are competing in and uncover any potential differences in physicality between professional and youth soccer players, to rationalise a need for continued physical development in youth soccer players and guide them towards the required professional standard. Despite empirical research having been performed in various modes (e.g., youth age comparisons, reliability studies, etc.) in soccer athletes, there is a lack of information available providing normative data and objective benchmarks for force plate tests of NMF in male professional and youth soccer players within the EFL. Equally, information specific to the reliability of measures and thus their utility as measures for monitoring acute changes in NMF in soccer players is not available. Consequently, researchers and practitioners working in soccer cannot identify practically meaningful and age-specific force platform derived force plate metrics to be prescribed for both these purposes.

3.8.1 Reliability Considerations

A test of reliability should consider both the absolute agreement (*absolute reliability*) [202] and degree of rank correlation (*relative reliability*) [203] between measurements [204]. To establish *absolute reliability*, the SEM approach is recommended, which is commonly reported as a CV and expressed as a percentage of the observed mean value [202]. The suggested statistical test to determine *relative reliability* is the ICC [203] which refers to the ability for a measure (e.g., JH) to maintain its rank within a cohort. In practice, it is essential to establish the *absolute reliability* of physical performance tests and the metrics of interest related to certain aspects of physical performance within each specific sport, and each independent athlete population (e.g., youth age groups), as this allows for the identification of whether an observed change in a measure represents a "meaningful" change in an athlete's performance [205]. Calculations of measurement error such as the MDC can be used in practice to determine meaningful change [202]. A change in a measure cannot be considered meaningful unless the change between the two testing points (e.g., pre- to post- a competitive match) is greater than the measurement error [205]. Thus, measures with greater error require a greater change in the observed value to provide confidence that a "true" change has occurred [205]. This is particularly important in professional sports when conducting physical performance tests on a frequent basis (e.g., daily or weekly "fatigue" monitoring) to immediately inform the coaching process of the MDT.

For *relative reliability*, a measure which yields a lower ICC value indicates a greater change in rank order between-sessions, indicating a poorer ability for a measure to rank athletes' performances across a squad. If a measure displays these traits, it would be insufficient in the ranking of physical capacity (e.g., in benchmarking) and tracking changes longitudinally within a squad of athletes [203]. It is common in youth team sports to work with homogenous groups (e.g., similar height, weight, capacity) and homogeneity may negatively affect the precision of relative reliability scores due to the potential of a reduced spread of scores across the group [206]. In such groups, there can be instances where the *absolute reliability* is good, where measures are considered to display low variability within a squad, but the *relative reliability* is poor. Therefore, it is important to assess both the absolute and relative reliability for key measurements, particularly if being used to monitor changes over time.

3.8.2 Issues in Benchmarking Research

A key issue with published normative data studies [27, 37-39] is that the reported data only represents the average of the population used, which limits the ability to determine what is a "good" performance within a cohort [40]. Recent research has recommended a novel approach to compiling and presenting normative data via the creation of objective benchmarks [114]. McMahon et al. [114] provided useful examples of how to create these for force plate metrics, utilising a grading system of standardised T-scores (scaled from 0 to 100), qualitative description (ranging from extremely poor to excellent), and a colour coded system to enhance interpretation. Age comparisons of normative data in professional English football clubs are available for a variety of force plate tests in female youth soccer players [37, 38], and available for only the IMTP in male youth soccer players [39]. However, much of this previous work compared groups with sample sizes less than has been suggested in related literature. For example, a study by Emmonds et al. [38] was conducted with a sample of one hundred and fifty-seven female youth soccer players. Although this seems like a relatively moderate sample, this sample was distributed across four age categories (U10, N =3 0; U12, N = 38, U14, N = 43, U16, N = 46) [38], yet previous research has estimated that sample sizes of greater than 85 (per group) are required for normative data studies, to generate stable means and SDs regardless of the degree of skewness in the dataset [207]. Such a sample may be sufficient with additional participants not necessarily affecting results, accruing additional time, cost and resources [208]. Given that specific force plate variables can discriminate between youth age groups in soccer [37-39], and between youth and professional levels in Rugby League [27], but a lack of comparison between male professional and youth soccer players exists, there is a requirement to fill this knowledge gap, with an appropriate sample size, and a better visualisation of data via the creation of objective benchmarks [114]. With the apparent lack of age comparisons between the youth and professional levels in male and female professional soccer, a study which provides comparative normative values of a variety of force plate tests for male youth and professional soccer players in English football clubs, and provides a statistical comparison between these age groups, seems warranted. A targeted approach to sampling enough subjects within each group is critical for sufficient confidence in normative data studies results.

3.8.3 Statistical Approaches to Data Reporting

Statistics is the science of collecting, classifying, analysing, and interpreting numerical data [41]. Accordingly, practitioners are advised to perform statistical functions when reporting force plate data, such as when creating comparisons and determining change over time. Typical statistical procedures include a variety of descriptive (e.g., central tendency, variability, and percentile rank), inferential (e.g., T-Test), and magnitude based (e.g., smallest worthwhile change, ES, etc.) [41]. The assumptions of normal distribution are often used to determine the utilised measures of central tendency and variability in data [209]. The Shapiro-Wilk test is commonly performed to determine if the data satisfied the assumptions of normal distribution [210]. It has been proposed that formal normality tests (e.g., the Shapiro-Wilk test) can be used from small (N < 50) to medium (N < 300) sized samples [211]. When utilising medium (N = 50 to 300) and large (N > 300) datasets to produce objective benchmarks, it also is recommended that a further combination of visual inspection, and assessments of skewness and kurtosis is performed to assess whether the assumption of normality is acceptable or not [211]. Skewness and kurtosis are measures of the asymmetry and 'peakedness' of a data distribution, respectively [211]. A "Z-Test" is utilised to assess normality using skewness and kurtosis [211]. This is done by dividing the skew values or "excess" kurtosis (provided by most statistical packages, e.g., SPSS) by their standard errors [211]. Standardised values for rejecting the null hypothesis need to be relative to the sample size utilised, because larger sample sizes typically result in smaller standard errors, therefore z-tests tend to be more easily rejected and accepted in large (> 300) and small (N < 50) samples, respectively [211]. For example, for a sample size classified as 'medium-sized' (N = 50 to 300), an absolute z-value of over 3.29 (alpha level 0.05) would be prescribed to conclude the distribution of the data in the sample as non-normal [211]. Following the determination of normal distribution, the mean and SD of each measure is traditionally utilised to create an objective benchmark unless the data unanimously reports non-normal distribution via formal normality testing (i.e., Shapiro-Wilks), skewness, and kurtosis. When specific measures do not satisfy these assumptions, researchers prefer reporting the median and interquartile range (IQR) as opposed to the frequently used mean and SD [209].

Standardised "Z-Scores" can be utilised to create objective benchmarks. Z-scores allow the visualisation of how an individual athlete performs in relation to the population mean, by determining how many SDs above or below the mean their score is [114]. When data is normally distributed, Z-Scores are applied based on the assumption that 99.7% of individual data points are recorded within three SDs (i.e., -3 to 3) of the mean value (i.e., corresponding to 0) [114]. These multiples of the SD are then utilised to create performance bands [114]. This is achieved by utilising the following formula:

Mean Value + (SD * Corresponding Z-Score)

[114].

Because the Z-Score grading description (i.e., -3 to 3 SDs) is not intuitive to athletes and coaches, standardised "T-Scores" have been proposed as an alternative standardised score which provide a scale of 0 to 100 (as opposed to -3 to 3), where a score of 50 (as opposed to 0) represents the mean value [114]. T-scores are calculated by utilising the following formula:

(Z-Score Value (e.g., -3) * 10) + 50

[114].

Descriptions of each banding have also been designed to provide an example of how to qualitatively interpret the objective benchmarks produced. McMahon et al. [114] proposed qualitative descriptions including Extremely Poor (< 20), Very Poor (20 to <30), Poor (30 to <40), Below Average (40 to <45), Average (45 to <55), Above Average (55 to <60), Good (60 to <70), Very Good (70 to <80), and Excellent (≥80). All this information can be produced using a Microsoft Excel spreadsheet (Microsoft Corp., Redmond, WA, USA).

For a measure to hold utility as an objective benchmark it must discriminate between two groups of interest (e.g., different competitive level and/or age category). Determining mean difference between groups is commonly performed through inferential statistics utilising specific statistical software such as SPSS (Chicago, IL, USA), and calculated via methods such as t-tests or one-way ANOVA and interpreting the test's results based on *p* values of 0.05 [23]. When reporting inferential statistics (e.g., T-Tests), it is recommended to include information about the obtained magnitude and the direction of the effect because the significance value only highlights a difference between two means without describing the magnitude of difference [210, 212]. In a review of articles published in the Journal of Experimental Psychology: General, from 2009 through 2010, Fritz and Morris [212] reported, following a T-Test, Cohen's *d* was the most commonly utilised ES. However, Cohen's *d* is sometimes referred to as the uncorrected ES, as it is calculated using the total sample average, resulting in a biased estimate of the population ES, particularly in research conducted with small (N < 20) or uneven sample sizes [213]. In the *d* family of ESs, the correction for Cohen's *d* is known as Hedges' *g* [213].

ESs are commonly interpreted as trivial (≤0.19), small (0.20 to 0.49), moderate (0.50 to 0.79), or large (≥0.80) [214].

When utilising force plate data for neuromuscular fatigue monitoring, it is recommended that attention be given to the specific statistical data analysis method used to determine acute change, to minimize the probability of error in the decision-making process [23]. Despite the simplicity and quickness of it, simply observing a raw value increasing or decreasing via central tendency statistics (e.g., mean, median, or mode) is not the recommended approach to determining difference [41]. Monitoring acute changes requires adept methods, however, some statistical methods (e.g., formal hypotheses testing) might not be sensitive enough to detect smaller changes in NMF on a weekly or daily basis or quick and efficient enough to perform in a practical setting (e.g., if requiring statistical software such as SPSS). Rather than using point values, an example which is both informative and feasible in a practical setting include the calculation of bandwidths of "normal" performance (e.g., utilising SDs to create SEMs and "z-scores"), which provides an upper and lower limit to determine change within [41, 57, 215].

3.9 Summary

The primary aim of the physical corner is to optimise physical preparedness, to increase the chances of outperforming opponents, reduce the likelihood of non-contact injury, and increase the potential of achieving sporting success [12]. This can be achieved by prescribing a programme which enhances fitness long-term (chronically) and minimises or allows time for effective recovery from fatigue in the short-term (acutely) [73, 74]. Being subject to neuromuscular fatigue (i.e., a reduction in maximal force-generating capacity) [121] is likely for soccer players who have to compete frequently with minimal recovery time (e.g., 48 to 72 hours later) due to congested fixture schedules [72, 74, 110]. During competition players are subject to considerable amounts of external workload, where authors have reported that EPL players covered an average total distance and high intensity running distance (≥19.8 km/h) of 10722 ± 978 m and 929 ± 305 m, respectively [17]. During competition, a combination of neuromuscular fatigue mechanisms are at play relating to both neural and contractile impairment [72, 74]. Such processes include central fatigue [122], neuromuscular junction inhibition [123], peripheral fatigue [124], and metabolic stress [104]. Thus, as physical profiling and fatigue monitoring is essential to physical coaches in soccer, having accurate [36], meaningful [31-35], and reliable [36] objective information on NMF, with normative data available for metrics of tests [30] which are practically feasible [23], is critical.

Single-joint assessment methods (e.g., isokinetic dynamometry) hold limited utility for monitoring changes in NMF, with issues regarding the standardisation of joint angle and angular velocity [154-156], non-uniform relative strength loss across joint angles when comparing short versus optimal versus long muscle lengths [147, 149-151], lack of ability to replicate the sports specific movement velocities of multi-joint movements, above 7 rad/sec [157], and the practical unfeasibility in team-sports where collecting a range of KPIs from various tests with ~20 athletes within a maximum 2 hour window would not be possible. The combination of points addressed here highlight why more systemic and dynamic evaluation approaches (i.e., via force plates) are a more contemporary practice for the determination of NMF [160, 161]. Evaluations of lower-body NMF assessments have been conducted with detailed analyses of multi-joint VJ and isometric tasks, where varying information on the validity [21, 57], reliability [58-61], meaningfulness (relation to sports specific actions) [32, 62-64], and discriminatory capabilities (i.e., for objective benchmarking) [27, 37-39] of specific metric is available. Future investigations into the utility of specific force plate variables by their ability to detect acute changes in NMF (i.e., their test-retest reliability) and ability to be utilised as objective benchmarks (i.e., their discriminatory capabilities of competitive levels and age groups) may prove useful to practitioners so that inferences can be drawn on the potential of specific tests and measures to be utilised a proxy for informing an athlete's current state of NMF and physical preparedness to inform training prescription. A dedicated overview of literature relating to the acute monitoring of changes in NMF using force plates is provided in Chapter 4 titled "Scoping Review of Methods of Monitoring Acute Changes in Lower Body Neuromuscular Function via Force Plates".

4 SCOPING REVIEW OF METHODS OF MONITORING ACUTE CHANGES IN LOWER BODY NEUROMUSCULAR FUNCTION VIA FORCE PLATES

4.1 INTRODUCTION

Practical and accurate technological solutions which boast validated hardware [21] and software [20] against criterion methods have contributed to an increased popularity of physical evaluation practices (e.g., physical profiling and fatigue monitoring) in sports, with many S&C coaches testing their athletes daily [22]. Taylor et al. [130] conducted a survey to identify contemporary physical evaluation practices by sports science practitioners in a variety of sports (e.g., rugby union, soccer, Australian rules football, swimming, track & field, etc.). Of 100 invites sent, 55% of practitioners responded, and 91% of these reported the use of some form of monitoring or evaluation of NMF in response to training or competition. The aims of these assessments were to prevent overtraining (22%), reduce the likelihood of non-contact soft-tissue injury (29%), determine the effectiveness of training programs (27%), and ensure the maintenance of performance throughout periods with high fixture congestion (22%) [130]. The methodologies of physical evaluation practices also varied, but the most utilised were self-reporting (e.g., daily wellness) questionnaires (84%), and tests which provided objective measures of NMF (61%) [130], performed on a monthly (33%), weekly (30%), or daily (6%) basis [130]. VJ tests were most frequently used (54%), where the CMJ test was utilised most frequently (N = 11), whilst the broad jump and SJ tests featured only once [130].

Objective measures are the most effective means of monitoring the magnitude and time course of acute changes in NMF [129]. The continuous monitoring of NMF on a weekly and/or daily basis can be used to determine neuromuscular fatigue and physical preparedness [19]. Additionally, if performed over the period of a season, continuous monitoring can be used to determine chronic developments in fitness [94, 216]. Continuous monitoring may be favourable in addition to the "traditional approach" of performing large scale fitness testing batteries 3-4 times per season (i.e., adopting a "combined approach") given that more frequent, smaller scale, testing sessions consisting of specific key measures will provide more data points within a given period, potentially resulting in more informative data trends in reports [94, 216], and providing a better understanding of individual injury risk [217, 218]. Force plates are amongst the most utilised technological apparatus for collecting objective measures of NMF in sports [130].

4.1.1 Data Collection Considerations

For force plate data to be beneficial [36], tests and metrics must (a) measure what they are supposed to (validity) [21], (b) relate to physical performance in competition (i.e., are meaningful) [23], and (c) be sensitive enough to detect change (high reliability and low measurement error) [36]. Additionally, specific to elite sports settings, tests are only useful for continuous monitoring if they are feasible in a practical setting. To ensure testing feasibility, examples of required characteristics include (d) quick and easy to perform (i.e. time-efficient) and (e) mechanically and metabolically non-fatiguing in nature (i.e., low physical demand) [31-34]. To add to this, coaches also value (f) the ability to immediately and appropriately analyse, interpret, and act upon testing data, which is a quality that is available via some force plate systems with integrated proprietary software [20]. Regarding the meaningfulness of measures, actions in sports typically utilise the SSC, where a muscle is first actively lengthened (eccentric action) followed by an immediate shortening (concentric action) [12, 117]. Consequently, lower-body NMF is commonly assessed via tests which utilise the SSC, such as VJ tests [130]. Common examples of VJ tests include the bilateral CMJ [219, 220], unilateral CMJ [45, 220], DJ [221, 222], and other variations of RJ [223, 224] tests. In regards to the sensitivity of measures to detect change [36], more technique-intensive tests exhibit greater data variability, and require more practice to produce consistency and reliability [36]. If a test requires a technique in which the athlete has not developed consistency, the test itself may fail to provide consistent results [225, 226].

In a recent scoping review, Guthrie et al. [23] examined the practices used for evaluating changes in physical preparedness longitudinally (e.g., pre- to post- training programme) within the football codes (i.e., rugby, soccer, American football, and Australian rules football). Guthrie et al. [23] identified the most frequently used test of NMF was the CMJ and suggested that this seems likely because of the test's ease, time-efficiency, and lack of resources required, leading to high compliance seen in the practical setting. Concentric-only (e.g., the SJ) [227] and isometric (e.g., the IMTP) [228] tests were reported as utilised less frequently [23]. A scoping review of methods used for the continuous monitoring of acute changes in NMF, and outside of the football codes, is yet to be performed. Athletes have a limited time to produce GRF in most competitive sports, so it is important to evaluate NMF using metrics which represent both the outcome (e.g., TOV and JH) and the strategy (e.g., time to take-off, countermovement depth, GCT, etc.) performed [15]. Gathercole et al. [65] also recommended utilising both outcome (e.g., JH) and strategy (e.g., time to take-off) metrics independently, given the explained time constraints in competitive sports, and because neuromuscular fatigue can manifest as an alteration in movement strategy highlighted by changes in temporal characteristics, without a change in outcome [116]. It is also important to consider kinetic measures as their generation throughout braking and propulsion is what dictates the movement strategy performed, and ultimately influences overall task outcome (i.e., TOV and JH) [182, 183]. Further, ratio measures such as the RSI in RJ tests and mRSI in the CMJ test have also been proposed in previous research as they incorporate factors relating to both the outcome (i.e., JH) and strategy (i.e., GCT and time to take-off, respectively) performed [66, 113, 224, 229].

Merrigan et al. [32] applied a RFR model to identify the metrics that were most influential to CMJ outcome (i.e., JH). Merrigan et al. [32] reported concentric duration, countermovement depth, and eccentric-to-concentric mean force ratio as the most significant predictors of JH, with a combined 91.7% explained variance. In practical terms, a deeper, faster, and more forceful strategy leads to a greater JH because, in VJ tasks, based on the impulse-momentum theorem, net propulsive impulse (propulsive force multiplied by propulsive phase time) relative to mass determined the vertical TOV of the COM [15], which determines JH [230]. Consequently, it is not surprising that the authors proposed these metrics relating to GRF production (i.e., eccentric-to-concentric mean force ratio) and strategy (i.e., concentric [also referred to as propulsion] duration and countermovement depth) as the most meaningful for evaluating NMF [32]. However, there is a reported mismatch between these proposed CMJ metrics and those most frequently used for evaluating changes in physical preparedness longitudinally, which Guthrie et al. [23] reported were JH (N = 6), FT (N = 2), FT:CT (N = 2), peak force (N = 1), peak power (N = 1), and relative peak power (N = 1).

When monitoring acute changes in NMF, the outcome of a VJ task is determined by relative propulsive impulse production [15, 231, 232]. However, significant ($p < 0.05$) reductions in body mass have been reported following both recreational (1.6 ± 0.2%) and professional (1.9 ± 0.2%) soccer matches, which would render outcome measures quite limited for detecting changes in NMF if body mass changes significantly across testing timepoints (e.g., pre- to post-match) [108]. This also extends to ratio metrics such as FT:CT and RSI, as outcome measures feature within their equations [59]. Additionally, mean and peak values (e.g., mean and peak force and power) are affected by changes in strategy, where an acute change to a more shallow and "stiffer" strategy can elicit greater peak forces over less time, and likely result in a reduced net propulsive impulse [184]. Thus, an alteration in strategy would likely alter peak force and make it hard to determine any potential reductions in NMF that may have been detected when using this metric had the strategy remained the same. For example, researchers have reported large increases in time to take-off (ES = 1.90) and eccentric time (ES = 1.91), along with decreases in absolute peak force (ES = 2.15) and eccentric-to-concentric mean power ratio (ES = 2.02), in CMJs at 30 minutes post-exercise (high intensity, interval style, stair climb protocol), but with a small increase in JH (ES = 0.47) [116]. This example strengthens the consideration to monitor more than outcome metrics as a small increase in outcome (i.e., JH) was observed (which could be deemed a positive change) but occurred due to changes in the performed strategy (e.g., increases braking and propulsive phase time and time to take-off), with a reduction in peak force [65, 116, 233]. To the author's knowledge, the commonality of use of force plate derived outcome, strategy, kinetic, and ratio metrics for monitoring acute changes in NMF is yet to be determined.

Regarding the sensitivity of measures to detect change [36], to enable force-time data collected at different time points to be reliably compared (i.e., in the monitoring process), data collection procedures must consist of the same equipment, tests, and testers (to limit intra-rater variability), and performed in the same environment (i.e., consistent flooring) [36]. Additionally, consistency in the zeroing of force plates between trials, cueing of technique (e.g., 'jump as fast and high as possible'), trial exclusion criteria (e.g., arm swing [AS] or tucking of the legs during a VJ [the latter does not matter if calculating JH from TOV]), and application of the pre-determined study design protocol (i.e., how many trials, over how many sessions?) in every testing session (i.e., over multiple time-points) is essential if utilising the data to monitor changes in NMF to inform training prescription [23]. It is also a requirement that testing sessions are performed with identical data collection procedures so that any difference between two sets of scores is limited to factors such as intra-subject (i.e., same subject) biological variability [36]. To the author's knowledge, the commonality of force plate data collection and testing standardisation procedures used for monitoring acute changes in NMF is yet to be determined. Consistency in the utilised and reported data collection and testing standardisation procedures in literature is essential to enable future comparisons of data (e.g., in meta-analyses), and would contribute towards the aim of promoting an accurate and consistent implementation of force plate testing in practice [23, 225].

4.2 AIMS

A variety of options are available to sports science practitioners to monitor acute changes in NMF using force plates, thus, researchers use different approaches regarding force plate test and metric selection [23]. The primary aim of this scoping review was to identify, map, and describe which practices exist in the context of monitoring acute (<1 week pre- to post-physical stimulus) changes in NMF using force plates. In a qualitative manner, the review will describe the similarities, differences, and gaps in the body of evidence retrieved regarding the specific force plate data collection, study design, and data analysis procedures employed. This knowledge will contribute towards forming a rationale for the data collection, study design, and data analysis protocols in future research on monitoring acute changes in NMF using force plates. To the author’s knowledge, no review currently exists which serves this purpose.

4.3 METHODS

4.3.1 Design

This scoping review followed the latest methodological guidance of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) extension for Scoping Reviews [234], with consideration for recommendations in research relating to scoping review protocols [234-237]. The objectives of this review were also developed considering the Population, Concept, Context (PCC) framework, as advised in a recent best practice reporting items protocol guide for the development of scoping reviews [235]. To allow for a broad identification of monitoring applications, the *population* specification was athletes of any sport (individual or team), participants whose occupation involved physical demand (i.e., the public services and military) in which the evaluation of NMF has been reported [222, 238], university students engaged in a sports team or course (e.g., sports science), and recreational athletes were also included. The research objective was to determine force plate methods previously used to monitor acute changes in NMF in daily or weekly monitoring or in response to a physical stimulus (e.g., a training session or competitive match). Based on this, acute, within-group, repeated measures design research was expected upon retrieval. A review protocol was not pre-registered for this review.

4.3.2 Literature Search

A Boolean/phrase search mode was applied using the following key words: "force plat*" AND "athlete" OR "player" OR "game" OR "match" OR "competition" OR "season" OR "sport" AND "monitoring" OR "testing" OR "evaluation" OR "assessment" OR "profiling" OR "benchmarking" OR "programming" OR "supercompensation". The keywords were inputted using this format into the following four databases: PubMed, EBSCO, Clarivate web of science, and Ovid. Filters were applied to all databases such as the key words were present in the topic (i.e., title, abstract, or key words) of studies written in the English language and presented in peer-reviewed academic journal articles. No restrictions were placed upon the age or sex of subjects. The search timeframe was not date restricted and was completed by 31st May 2023.

4.3.3 Inclusion and Exclusion Criteria

All duplicates were removed initially with the remaining studies then being screened utilising the following inclusion criteria. The inclusion criteria were applied in three stages (Figure 4.1).

Initially, a *first level* criterion was applied where research articles were deemed eligible provided that the study (1) was written in the English language, (2) reported the use of force-plates, (3) reported the purpose of testing was to assess *lower-body* NMF, (4) reported the purpose of testing was to identify physical capacity (fitness) or an acute or chronic response to a stimulus (fatigue or fitness, respectively), and (5) reported testing a physically abled population. Articles were excluded if the study (1) was not written in the English language, (2) did not clearly report the use of force-plates, (3) did not report the use of *lower-body* assessments or reported only *upper-body* assessments, (4) reported a purpose of testing other than to identify to identify physical capacity (fitness) or a response to a stimulus (fatigue), such as for rehabilitation progression, concussion recovery, balance or gait, and (5) reported testing with a population with a physical disability. All reviews and validation studies (e.g., force-plates vs linear position transducers) were excluded. *The results from the first stage were sent to HD Inc. to form a "force plate research catalogue" as part of the iPhD agreement.*

A *second level* inclusion criterion was then applied, where research articles were deemed eligible provided that the study (1) reported more than one testing session was performed, and (2) reported a focus on monitoring *changes* in NMF. Studies were excluded if the study (1) reported the use of only a single testing session, or (2) reported a focus other than monitoring *changes* in NMF, such as changes in biological maturation or developments in a specific sports task (e.g., golf drive kinetics).

A *third level* inclusion criterion was then applied, where the remaining studies were categorised as focused on acute (<1 week between physical activity and re-test) or chronic (>1 week between physical activity and re-test) changes in NMF. The remaining acute studies (N = 11) were taken forward for review, and as performed in recent similar research [23], the reference lists of these studies were then examined for additional studies that could be included in the review (Figure 4.1).

4.3.4 Analysis and Interpretation of Results

After the inclusion criteria was applied the remaining studies were evaluated and reported. As performed in recent similar research [23], the information extracted from studies was primarily qualitative, which included demographics (e.g., sport, sex, age, height, mass, competitive level, experience), descriptive data collection information (e.g., number of tests and metrics used, frequency of testing, timelines of testing, time of season, verbal cues, surface, familiarisation, warm-up, zeroing of force plates, and weighing of subjects), activity information (e.g., activity performed and measures of quantifying TL), force-plate hardware used, and data analysis procedures (i.e., calculations including differences in metric definitions). Quantitative information was extracted from these studies only to identify how many studies provided sufficient results information (i.e., mean and SD) at each time point. This quantitative data served to allow for subsequent discussions of information regarding data collection, metric selection, and data analysis procedures. If sufficient data was not provided within the publication, the authors of the studies were contacted via e-mail for the missing information.

4.4 RESULTS

4.4.1 Search Results

One thousand, eight hundred, and twenty-nine studies were identified within the four databases, with 1004 studies being duplicates and therefore removed prior to the application of the inclusion criteria (Figure 4.1). Eight hundred and twenty-five studies were assessed for eligibility using the inclusion criteria, identifying 718 studies as ineligible (Figure 4.1). Of the remaining 38 articles, 12 were deemed as focused on 'acute' changes and 26 on 'chronic' changes in NMF. For this review, the acute studies were taken forward for further inspection, as a recent similar scoping review has already been performed with a longitudinal focus [23]. Upon further inspection, one study was identified as removed from circulation therefore the remaining acute studies included in this review is 11. After examining the reference lists of the remaining studies, an additional eleven studies were identified as appropriate to use in this review. Therefore, the remaining total of studies used in this review is 22 [43-49, 52-56, 65, 98, 116, 233, 239-244]. Studies are all of within-group repeated measures design (Figure 4.1).

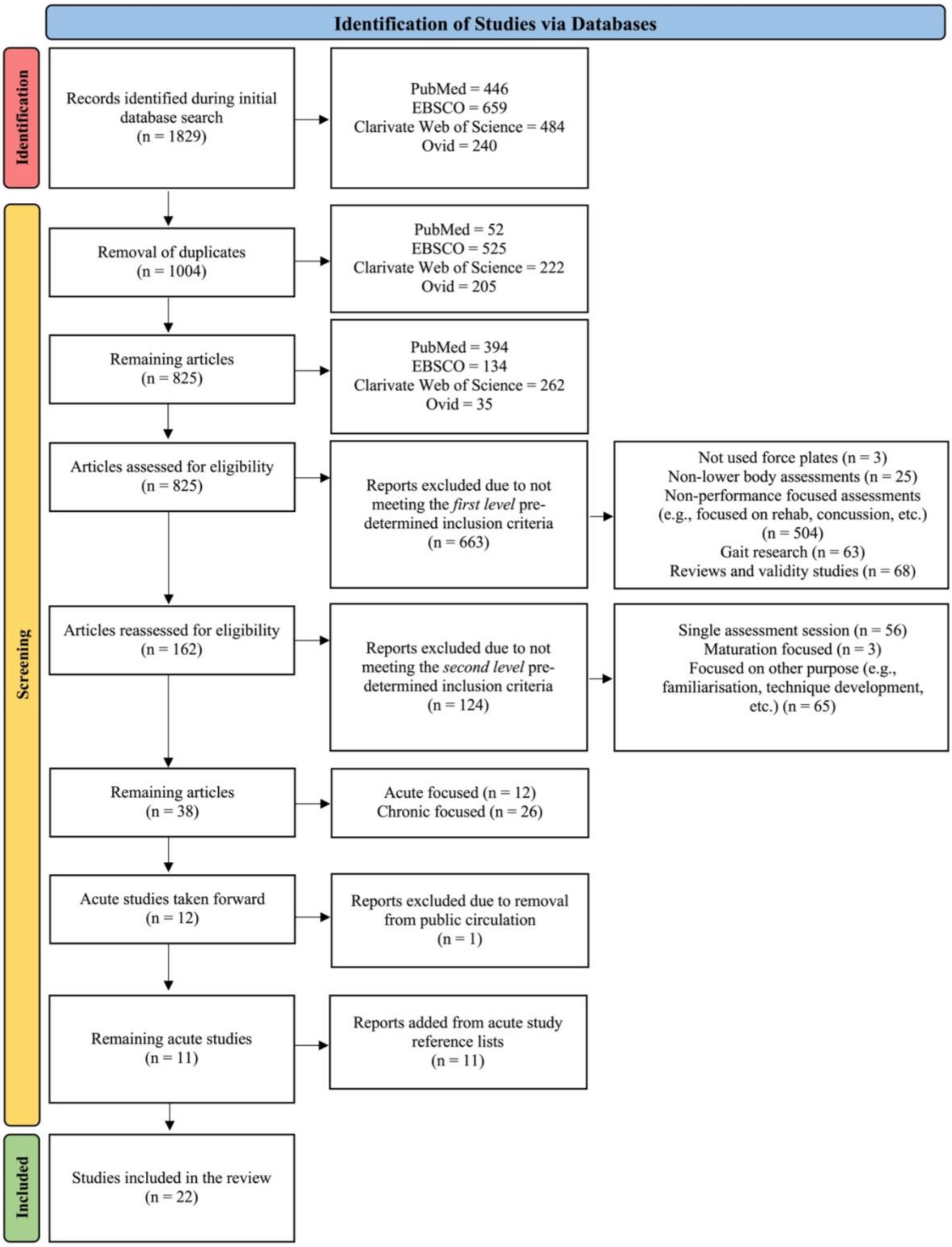

Figure 4.1. Flowchart illustrating the study selection process.

4.4.2 Summary of Demographics

From the 22 articles assessed in this study, 319 participants were utilised resulting in an average sample of 14.5 ± 5.7 participants per study (Table 4.1). The average age, height, and mass of participants in these studies was 23.2 ± 4.4 years, 181.7 ± 7.6 cm, and 82.4 ± 15.6 kg, respectively (Table 4.1). Regarding the demographics of participants, 19 studies included male (N = 256) participants, 3 studies included female (N = 31) participants, and 3 studies did not specify the participants' sex (N = 32) (Table 4.1). Consequently, male and female participants made up 80.25% and 9.71% of the total population of all studies, respectively, and 10.03% were not specified (Table 4.1).

Of these 22 studies, 19 studies specified the use of a population engaged in competitive sports, 2 studies with mixed recreational sports athletes, and 1 study with military personnel (Table 4.1). Of the competitive sports populations, 16 studies recruited team sports athletes (e.g., soccer), and 3 studies recruited individual sports athletes (i.e., triathlon, snowboard cross, and powerlifting athletes) (Table 4.1). The most frequent competitive sports were rugby union (N = 5), rugby league (N = 2), soccer (N = 2), and handball (N = 2), all of which are team sports (Table 4.1).

Based on competition level, 10 studies defined their sample as "elite" or full-time professional athletes (i.e., "senior" level), and 5 studies used participants which were considered "youth" or academy level (Table 4.1). The senior and youth athletes had an average age of 24 ± 2.5 years and 17.3 ± 1.2 years, respectively (Table 4.1). Finally, 7 studies reported training or playing experience, and 15 studies did not (Table 4.1).

Table 4.1. Summary of Demographics.

Author(s)	Occupation / Sport	Sample	Groupings	Sex	Age (years)	Height (cm)	Body Mass (kg)	Competitive Level	Experience
Bedo et al. [2020]	Handball	20	N/A	Female	21.9 ± 3.4	176 ± 7	63.5 ± 9.1	N	7.2 ± 3.2 Playing Years
Boullosa et al. [2011]	Runners and Triathletes	22	16 = Runners 6 = Triathletes	8 Runners = Male 8 Runners = Female 6 Triathletes = Male	Male Runners: 24 ± 4.3 Female Runners: 22.5 ± 5.5 Male Triathletes: 28.5 ± 6.2	Male Runners: 179 ± 8 Female Runners: 165 ± 6 Male Triathletes: 175 ± 5	Male runners: 68.4 ± 7.5 Female runners: 53.9 ± 3.8 Male triathletes: 67.2 ± 4.1	Mixed from "Regional" to "Rlite"	N
Lonergan et al. [2018]	Rugby Union	14	7 = < 24 Months Post ACL Reconstruction 7 = Non-injured	Male	Injured: 23 ± 3 Non-injured: 26 ± 3	Injured: 186 ± 4 Non-injured: 184 ± 7	Injured: 104 ± 7 Non-injured: 95 ± 7	Mixed with English Premiership, Championship, and National League 1	> 10 Playing Years > 2 Weeks Experience to Testing Task
Lupo et al. [2021]	Rugby Union	9	6 = Backs 3 = Forwards	Male	Backs: 21 ± 1 Forwards: 20 ± 2	Backs: 182 ± 6 Forwards: 188 ± 5	Backs: 86 ± 7.4 Forwards: 97.2 ± 6.2	Italian Serie A	> 8 Playing Years
Scanlan et al. [2017]	Basketball	10	N/A	Male	16.6 ± 1.1	182.4 ± 4.3	68.3 ± 10.2	Junior Level	N
McLellan et al. [2012]	Rugby League	15	8 = Forwards 7 = Backs	Male	24.2 ± 7.3	188 ± 20.1	94.6 ± 26.8	"Elite" National Rugby League	N
Thorlund et al. [2008]	Handball	10	N/A	Male	22.8 ± 1.5	188.4 ± 2.7	91.7 ± 3.0	"Elite" Danish National League	N
Gathercole et al. [2015]	"Team Sports"	11	N/A	Male	23.8 ± 3.9	182 ± 6	80.3 ± 6.6	College Level	N

Table 4.1. (Continued).

Author(s)	Occupation / Sport	Sample	Groupings	Sex	Age (years)	Height (cm)	Body Mass (kg)	Competitive Level	Experience
Kennedy et al. [2017]	Rugby Union	9	N/A	Male	19.0 ± 1.5	188.3 ± 1.5	95.0 ± 10.5	"Elite" Academy Level	N
McLean et al. [2010]	Rugby League	12	N/A	Male	24.3 ± 3.6	184.7 ± 6.1	101.9 ± 8.4	South Sydney Rabbitohs National Rugby League Team	69 ± 65 National Rugby League Matches
Roe et al. [2016]	Rugby Union	14	N/A	Male	17.4 ± 0.8	182.7 ± 7.6	86.2 ± 11.6	Professional Rugby Union Academy	N
Yu et al. [2020]	Mixed Recreational Sports University Students	15	N/A	Male	23.93 ± 0.80	176.70 ± 2.75	73.93 ± 4.76	N/A	N
Gathercole et al. [2015]	Snowboard Cross	7	N/A	4 = Male 3 = Female	Male: 26.5 ± 5.8 Female: 26 ± 6.1	Male: 183.4 ± 3.8 Female: 165.7 ± 4.4	Male: 86.2 ± 3.4 Female: 64.4	"Olympic-caliber"	N
Oliver et al. [2008]	Soccer	10	N/A	Male	15.8 ± 0.4	173 ± 6	59.8 ± 9.7	Amateur Youth Soccer Clubs	N
Clarke et al. [2015]	Canadian Football	15	N/A	Male	21.8 ± 1.6	187.2 ± 5.2	97.6 ± 14.7	University of Saskatchewan	N
West et al. [2014]	Rugby Union	14	N/A	Male	24.9 ± 4.4	185 ± 1	105.2 ± 12.3	Full-time Professional Celtic League and European Cup	N

Table 4.1. (Continued).

Author(s)	Occupation / Sport	Sample	Groupings	Sex	Age (years)	Height (cm)	Body Mass (kg)	Competitive Level	Experience
Merrigan et al. [2021]	Diplomatic Security Deployment Special Agents	13	N/A	N	37 ± 5	202.11 ± 28.71	71.67 ± 3.81	N/A	> 2 Years Consistent Physical Training
Horita et al. [1999]	Mixed Recreational Sports	10	N/A	Male	28 ± 4	180 ± 6	78 ± 9	N/A	N
McCall et al. [2015]	Soccer	29	23/29 Reliability Assessment 11/29 Sensitivity Assessment	Male	19.6 ± 3.5	181 ± 6	74.3 ± 7.4	French League 1 & Champions League	N
Travis et al. [2021]	Powerlifting	19	Assigned to +3 Days (n = 10) or +5 Days (n = 9) Re-test	N	23.8 ± 4.1	174.2 ± 7.3	90.8 ± 20.7	N	N
Bromley et al. [2021]	Soccer	14	N/A	Male	17.6 ± 0.5	177 ± 8	63.2 ± 6.7	Academy Category 3	> 2 Years Soccer and Resistance Training Experience
Troester et al. [2019]	Rugby Union	27	10 Backs 17 Forwards	Male	26 ± 3	189 ± 6	106 ± 14	Full-time professional	46 ± 22 Super Rugby League matches

Key: cm, centimetres; kg, kilograms; N, information not provided; N/A, not applicable.

4.4.3 Summary of Data Collection Protocols

From the 22 articles assessed in this study, the tests utilised were the CMJ (N = 16), DJ (N = 3), SJ (N = 1), isometric posterior lower-limb muscle test (N = 1), isometric squat test (N = 1), unilateral CMJ (N = 2), and unilateral drop landing (N = 1) (Table 4.2). Of the studies involving competitive sports populations (N = 19), most of the testing took place during the in-season period (N = 14) in comparison to the pre-season period (N = 1), whilst some did not specify when within the season the testing was done (N = 4) (Table 4.2). Regarding the standardisation of testing procedures, 16 studies defined the use of verbal cueing for testing, whilst 6 did not. The most common trial instructions used included "hands-on-hips" (N = 10), "jump as high as possible" (N = 10), and with a "self-selected countermovement depth" (N = 12) (Table 4.2). Additional considerations for the standardisation of testing were described in some studies, such as a description of the surface used (N = 1), footwear prescribed (N = 4), details of familiarisation protocol (N = 14), details of prescribed warm-up prior to testing (N = 13), zeroing of force plates prior to each test (N = 3), and the process of weighing participants prior to each test trial (N = 3) (Table 4.2).

Fourteen different force plate models were identified, across 7 different providers (Table 4.3). The most frequently used force plate provider was Kistler Instruments Ltd (N = 8), followed by Fitness Technology (N = 5), and American Mechanical Technology Inc. (AMTI) (N = 3) (Table 4.3). The most frequently used force plate model was the 400 Series Performance Plate (Fitness Technology, Adelaide, Australia) (Table 4.3). There were 7 different data collection frequencies used, and the most popular was 1000 Hz (N = 10), the highest was 5000 Hz (N = 1), and the lowest was 200 Hz (N = 3) (Table 4.3).

Table 4.2. Summary of Reported Data Collection Protocols.

Author(s)	Test	Time of Season	Verbal Cues	Surface Used?	Footwear?	Familiarisation?	Warm-Up?	Zeroing?	Weighing?
Bedo et al. [2020]	CMJ	N	N	N	N	N	N	N	N
Boullosa et al. [2011]	CMJ	Runners: Immediately Post-season Triathletes: Mid- to End-season	Maximal effort CMJ Jump as high as possible Countermovement depth freely chosen	N	N	Y	N	N	N
Lonergan et al. [2018]	Bilateral CMJ Unilateral CMJ	In-season	Hands on hips Jump as fast and high as possible Self-selected countermovement depth	N	N	N	N	N	N
Lupo et al. [2021]	CMJ	In-season	Hands on hips Jump with freely chosen strategy	N	N	N	N	N	N
Scanlan et al. [2017]	CMJ	N	Hands on hips Jump as high as possible Self-regulated countermovement depth	N	N	Y	Y	N	N
McLellan et al. [2012]	CMJ	In-season	Arm swing utilised Jump as high as possible Arm swing technique and countermovement depth was self-determined	N	N	Y	Y	N	N
Thorlund et al. [2008]	CMJ	In-season	Hands on hips Make a fast downward movement to about 90 degrees knee flexion immediately followed by a fast upward movement Jump as high as possible	N	N	Y	Y	N	N
Gathercole et al. [2015]	CMJ	N	N	N	N	Y	Y	Y	N

Table 4.2. (Continued).

Author(s)	Test	Time of Season	Verbal Cues	Surface Used?	Footwear?	Familiarisation?	Warm-Up?	Zeroing?	Weighing?
Kennedy et al. [2017]	CMJ	In-season	Hands on hips Jump as high as possible Countermovement depth was self-determined	N	N	N	Y	Y	Y
McLean et al. [2010]	CMJ	In-season	Hands on hip Jump as high as possible Self-selected countermovement depth	N	N	Y	Y	N	N
Roe et al. [2016]	CMJ	In-season	Hands on hips Jump as a high as possible Countermovement depth was self-determined	N	N	N	Y	N	N
Yu et al. [2020]	CMJ	N/A	N	N	Y	N	N	Y	N
Gathercole et al. [2015]	CMJ	In-season	N	N	N	Y	Y	N	N
Oliver et al. [2008]	CMJ DJ SJ	In-season	Hands on hips for all jumps CMJ: Jump as high as possible Countermovement depth was self-selected SJ: Jump as high as possible from 90 deg knee flexion angle and without a countermovement DJ: Drop from a height of 0.35 m and then jump as high as you can as soon as possible after landing	N	N	Y	N	N	N
Clarke et al. [2015]	CMJ	Pre-season	Hands on hips Jump as high as possible No directions were given regarding movement speed or countermovement depth	N	Y	Y	Y	N	N
West et al. [2014]	CMJ	In-season	Hands on hips Self-selected countermovement depth "Explode" upwards and jump as high as possible	N	N	Y	Y	N	Y

Table 4.2. (Continued).

Author(s)	Test	Time of Season	Verbal Cues	Surface Used?	Footwear?	Familiarisation?	Warm-Up?	Zeroing?	Weighing?
Merrigan et al. [2021]	DJ	N/A	Step off (not walk or jump off) the box and immediately perform a maximal effort countermovement jump with little ground contact	N	N	Y	Y	N	N
Horita et al. [1999]	DJ	N/A	N	N	N	N	N	N	N
McCall et al. [2015]	Isometric Posterior Lower-limb Muscle Test	In-season	The player pushed their heel into the force platform as hard as possible without lifting their buttocks, hands or head off the mat Verbal encouragement was given	N	Y	Y	Y	N	N
Travis et al. [2021]	Isometric Squat	N/A	N	N	N	N	N	N	N
Bromley et al. [2021]	Unilateral CMJ	In-season	Hands on hips Self-selected countermovement depth Maximal effort to jump as fast and as high as possible The non-jumping limb was required to remain slightly flexed at the hip and knee, so that the foot was hovering approximately parallel to the midshin of the jumping limb, with no swinging allowed	N	N	Y	Y	N	Y
Troester et al. [2019]	Unilateral Drop Landing (from CMJ Height)	In-season	Participants started at a point 1 metre from the centre of the force plate Jump as high as possible off two legs and stick and hold the landing on one leg If the landing foot moved after contact or the opposite foot touched down, trails were discarded	Y	N	Y	N	N	N

Key: CMJ, countermovement jump; DJ, drop jump; SJ, squat jump; Y, information provided; N, information not provided; N/A, not applicable.

Table 4.3. Tally Illustrating Hardware Used.

References	N	Hardware	Sampling Frequency
Gathercole et al. [2015a]	5	400 Series Performance Plate Fitness Technology Adelaide, Australia	200 Hz
McLean et al. [2010]			200 Hz
Gathercole et al. [2015b]			200 Hz
Roe et al. [2016]			600 Hz
Bromley et al. [2021]			600 Hz
Thorlund et al. [2008]	2	Model 9281B Kistler Instruments Ltd Winterthur, Switzerland	1000 Hz
Yu et al. [2020]			
McCall et al. [2015]	2	Model 9260AA6 Kistler Instruments Ltd Winterthur, Switzerland	1000 Hz
Troester et al. [2019]			
Horita et al. [1999]	2	Not Described	Not Described
Travis et al. [2021]			
Boullosa et al. [2011]	1	Quattro Jump Kistler Instruments Ltd Winterthur, Switzerland	500 Hz
Lupo et al. [2021]	1	Model *not stated* Kistler Instruments Ltd Winterthur, Switzerland	2048 Hz
Kennedy et al. [2017]	1	Model 9286BA Kistler Instruments Ltd Winterthur, Switzerland	1000 Hz
West et al. [2014]	1	Model 92866AA Kistler Instruments Ltd Farnborough, United Kingdom	N
Scanlan et al. [2017]	1	BP400800-2000 American Mechanical Technology, Inc Watertown, MA, USA	1000 Hz
Oliver et al. [2008]	1	OR6-5 American Mechanical Technology, Inc Watertown, MA, USA	1000 Hz
Merrigan et al. [2021]	1	AccuPower American Mechanical Technology Inc Watertown, MA, USA	1600 Hz
Bedo et al. [2020]	1	A/D converter #USB-6251-BNC National Instruments Austin, TX, USA	5000 Hz
Lonergan et al. [2018]	1	PS 2141 Pasco Roseville, CA, USA	1000 Hz
McLellan et al. [2012]	1	ONSPOT 200-1 Innervations Muncie, IN, USA	1000 Hz
Clarke et al. [2015]	1	Na4060-10 Bertec Columbus, OH, USA	1000 Hz

Key: Hz, hertz; N, information not provided.

4.4.4 Summary of Study Design

Six of the 22 studies did not include sufficient results information for their measures (i.e., means and SDs for a metric of each test at each time point), meaning a detailed summary of study design information was only possible for 16 studies [44, 45, 47-49, 52-55, 65, 98, 116, 233, 239, 240, 244]. The assessments utilised in these 16 studies included the CMJ (N = 11), DJ (N = 3), SJ (N = 3), unilateral CMJ (N = 1), unilateral drop landing (N = 1), and the "isometric posterior lower-limb muscle test" (N = 1) (Table 4.4).

Of the 16 studies, 6 different baseline (pre-activity) testing timepoints were reported, which were –24 h (N = 1), -2 h (N = 1), –30 min (N = 2), -15 min (N = 1), –2 min (N = 3), and –0 min (N = 9) (Table 4.4). Additionally, 12 different post-activity testing timepoints were reported, which were +0 min (N = 7), +2 min (N = 3), +15 min (N = 1), +30 min (N = 2), +1 h (N = 1), +2 h (N = 1), +24 h (N = 5), +48 h (N = 3), +72 h (N = 3), +96 h (N = 2), +120 h (N = 1), and +1 week (N = 2) (Table 4.4).

The effects of 6 different activities on NMF were identified, which were categorised as a usual rugby union training microcycle (i.e., a regular week of usual outdoor and indoor training sessions and competitive match-play) (N = 1), usual competitive match-play only (N = 2 soccer, n = 1 rugby league), a usual outdoor (field-based) rugby union training session only (N = 2), a pre-determined training session designed to simulate competitive match demands (N = 1 basketball, N = 1 handball, N = 1 Canadian football), a pre-determined High-Intensity Interval Training (HIIT; gym-based) fatigue protocol (N = 2), and a standardised cardiovascular fitness test (i.e., incremental treadmill running test) (N = 5) (Table 4.4).

TL was quantified using time (seconds or minutes) (n = 3), Maximal Aerobic Speed (MAS; km/h) (N = 1), external TL values (i.e., total distance covered, running, fast running, and sprinting distance; m) (N = 7), average speed (metres/min) (N = 1), number of rounds performed (N = 1), number of sport-specific actions performed (i.e., jump shots and feints) (N = 2), repetitions performed to volitional exhaustion (N = 1), internal TL values (i.e., average and maximum HR; bpm) (N = 2), and total time at maximal exertion (s) (N = 1). Of these 16 studies, TL was not quantified in 6 studies (Table 4.4).

Table 4.4. Summary of Study Design.

Author(s)	Test	Activity Performed	Activity Measures	Mean ± SD	Baseline	Post-Intervention
Boullosa et al. [2011]	CMJ	Université de Montréal Track Test	Time (s) MAS Value (km/h)	1476 ± 145 18.9 ± 1.2	- 2 min	+ 2 min
Lupo et al. [2021]	CMJ	Regular Training Session (Rugby Union)	Total Distance Covered (m) Average Pace (metres/min)	With Tackles: 5020 ± 253 No Tackles: 6270 ± 216 With Tackles: 59.7 ± 1.91 No Tackles: 64.2 ± 1.66	- 0 min	+ 0 min
Scanlan et al. [2017]	CMJ	Basketball Exercise Simulation Test	Time (min) Rounds Performed	40 80	- 2 min	+ 2 min
McLellan et al. [2012]	CMJ	8 Separate Competitive Matches (Rugby League)	N	N	- 24 h - 30 min	+ 30 min, + 24 h + 48 h, + 72 h + 96 h, + 120 h
Thorlund et al. [2008]	CMJ	Simulated Handball Match	Running (m) Fast Running (m) Sprinting (m) Jump Shots (number) Feints (number) Total Distance Covered (m)	594.3 401.25 247.00 28 56 6527.20	- 0 min	+ 0 min
Gathercole et al. [2015]	CMJ	High-intensity Intermittent-exercise Running Test	Total Distance Covered (m)	8613 ± 1249	- 0 min	+ 0 min + 24 h + 72 h

Table 4.4. (Continued).

Author(s)	Test	Activity Performed	Activity Measures	Mean ± SD	Baseline	Post-Intervention
Kennedy et al. [2017]	CMJ	3 Regular High-intensity Training Sessions (Rugby Union)	N	N	- 0 min	+ 24 h + 48 h
Yu et al. [2020]	CMJ	Standardised Treadmill Running Test	N	N	- 0 min	+ 0 min
Gathercole et al. [2015]	CMJ	Intermittent High-intensity Stair-climb Fatigue Protocol	Total Time at Maximal Exertion (s)	375	- 30 min	+ 30 min
Oliver et al. [2008]	CMJ DJ SJ	Intermittent High-intensity Exercise Test on Non-motorised Treadmill	Total Distance Covered (m) Average Heart Rate (bpm)	4745 ± 102 173 ± 12	- 0 min	+ 0 min
Clarke et al. [2015]	CMJ	Canadian Football G-sim	Maximum Heart Rate (bpm)	187.5 ± 9.3	- 0 min	+ 0 min + 24 h + 48 h
Merrigan et al. [2021]	DJ	Incremental Treadmill Running Test	Time (min)	7 to 10	- 2 min	+ 2 min

Table 4.4. (Continued).

Author(s)	Test	Activity Performed	Activity Measures	Mean ± SD	Baseline	Post-Intervention
Horita et al. [1999]	DJ	Continuous Rebound Jump Fatigue Protocol on a Sledge Apparatus at 23 Degrees Incline	Repetitions to Exhaustion (number)	117 ± 70	- 0 min	+ 0 min + 2 h + 96 h
McCall et al. [2015]	Isometric Posterior Lower-limb Muscle Test	Competitive Match (Soccer)	N	N	- 15 min	+ 15 min + 1 wk
Bromley et al. [2021]	Unilateral CMJ	A Single 90 Minute Competitive Match (Soccer)	N	N	- 2 h	+ 1 h + 24 h + 72 h
Troester et al. [2019]	Unilateral Drop Landing (from CMJ Height)	A Reuglar Training Week and Weekend Competitive Match (Rugby Union)	N	N	- 0 min	+ 1 wk

Key: CMJ, countermovement jump; DJ, drop jump; SJ, squat jump; SD, standard deviation; s, seconds; km, kilometres; wk, week; h, hour; m, metres; min, minute; bpm, beats per minute; N, information not provided.

4.4.5 Summary of Measures

As described above, a detailed summary of measures used was only possible for the 16 studies which presented sufficient results information (Tables 4.5-4.9) [44, 45, 47-49, 52-55, 65, 98, 116, 233, 239, 240, 244], where 52 different metrics were reported across the 11 studies which utilised the CMJ (Table 4.5), which equates to an average of 4.73 metrics per study. The measures which were reported more than once across these studies, in order of most to least frequent, were JH (N = 7), peak force (N = 7), peak power (N = 6), mean force (N = 4), mean power (N = 4), eccentric phase time (N = 4), concentric phase time (N = 4), peak velocity (N = 3), total movement time (N = 3; sometimes referred to as time to take-off or contraction time [CT]), force at 0 velocity (N = 3), "area under the force-velocity trace" (N = 3), TOV (N = 2), peak concentric force (N = 2), RFD (N = 2), "mean eccentric and concentric power over time" (N = 2), FT (n = 2), and FT:CT (N = 2) (Table 4.5). These 52 CMJ metrics could also be categorised based on relating to outcome (N = 2; 3.8%), force (N = 20; 38.5%), work and power (N = 10; 19.2%), velocity (N = 5; 9.6%), and strategy (i.e., displacement and time) (N = 15; 28.8%) (Table 4.5). A metric calculation was not provided for 11 metrics (Table 4.5). Varying calculations were identified for metrics such as JH (N = 4), peak force (N = 2), peak concentric force (N = 2), RFD (N = 2), peak power (N = 4), eccentric phase time (N = 2), concentric phase time (N = 2), and FT (N = 2) across studies (Table 4.5). A metric calculation was utilised for different metric definitions in some studies. The greatest vertical force produced during the propulsion phase of the CMJ test was defined as peak force (N = 2) and peak concentric force (N = 2) in separate studies (Table 4.5). The time required to perform both the eccentric and concentric phases of the CMJ tests was defined as total movement time and take-off phase time in separate studies (Table 4.5).

For the DJ, 15 different metrics were reported across the 3 studies which utilised the test (average of 5 metrics per study) (Table 4.6). The measures which were reported more than once across these studies were peak force (N = 2) and contact time (N = 2) (Table 4.6). A metric calculation was not provided for 9 metrics (Table 4.6). Varying calculations were identified only for contact time (N = 2) (Table 4.6). For the SJ, the single study which utilised the test reported 5 metrics (Table 4.7). These metrics were peak force, mean force, propulsive force, contact time, and FT (Table 4.7). A metric calculation was not provided for 3 metrics (Table 4.7). For the unilateral assessments, 14 different metrics were reported across the 2 studies which utilised the test (average of 7 metrics per study), and all measures only featured once across these studies (Table 4.8). For the "isometric posterior lower-limb muscle test", the single study which utilised the test reported 1 metric, which was peak force (Table 4.8). A metric calculation was not provided for 4 metrics (Table 4.8). Varying terminology for phase definitions [25] were identified within studies, such as braking (N = 2), eccentric (N = 8), propulsive (N = 4), and concentric (N = 14) used across all tests (Tables 4.5 to 4.8).

Table 4.5. Tally Illustrating Countermovement Jump Metric Selection and Calculation Methods.

References	Test	Metric	N	Calculation
Kennedy et al. [2017]	CMJ	Flight Time Alternative Contraction Time Ratio (AU)	1	The ratio of flight time to alternative contraction time. Alternative contraction time was determined by calculating the peak relative eccentric power and data points within a 10% range on the power-time trace, and then completing a backward search of consecutive time points until the power change is < 0.15 W/kg for more than 4 out of 5 consecutive pairs.
Gathercole et al. [2015b] Kennedy et al. [2017]	CMJ	Flight Time Contraction Time Ratio (AU)	2	The ratio of flight time to contraction time. Contraction time is the duration from jump initiation to take-off.
Boullosa et al. [2011]	CMJ	Jump Height (cm)	7	Height of the center of mass at the apex minus at the point of take-off.
Scanlan et al. [2017]				Via the flight time method (1/2 gravitational acceleration * (flight time / 2)^2).
Thorlund et al. [2008]				Via the take-off velocity method (TOV^2 / 2 * gravitational acceleration).
Gathercole et al. [2015a] Kennedy et al. [2017] Gathercole et al. [2015b]				The maximum jump height achieved, calculated using peak velocity.
Yu et al. [2020]				Via the flight time method (gravitational acceleration^{-2} * flight time^2) / 8.
Thorlund et al. [2008]	CMJ	Take-off Velocity (m/s)	2	Not described.
Clarke et al. [2015]				Integration of the GRF data, combined with body mass, allowed calculation of the vertical velocity profile, which was used to obtain TOV.
Gathercole et al. [2015b]	CMJ	Flight Time (s)	2	Time spent in the air from jump take-off to landing.
Oliver et al. [2008]				The time between when force was < 10 N (instant of take-off) and when force returned to < 10 N (instant of touch-down).

Table 4.5. (Continued).

References	Test	Metric	N	Calculation
Boullosa et al. [2011]	CMJ	Vertical COM displacement (cm)	1	Not described.
Thorlund et al. [2008]	CMJ	Concentric Displacement (cm)	1	Maximal centre of mass displacement during positive velocity.
Thorlund et al. [2008]	CMJ	Eccentric Displacement (cm)	1	Maximal centre of mass displacement during negative velocity.
Gathercole et al. [2015b]	CMJ	Time to Peak Power (s)	1	Time from jump initiation to peak power.
Gathercole et al. [2015b]	CMJ	Time to Peak Force (s)	1	Time from jump initiation to peak force.
Oliver et al. [2008]	CMJ	Contact Time (s)	1	The period between when force change by more than 10 N from resting body weight (initiation of movement), to when force was < 10 N (instant of take-off).
Gathercole et al. [2015a] Kennedy et al. [2017] Gathercole et al. [2015b]	CMJ	Total Movement Time (s)	3	Time required to perform the entire CMJ (ie, both eccentric and concentric phases).
Thorlund et al. [2008]	CMJ	Take-off Phase Time (ms)	1	Eccentric plus concentric phase time.
Thorlund et al. [2008]	CMJ	Concentric Phase Time (s)	4	Total time of positive velocity prior to take-off.
Gathercole et al. [2015a] Kennedy et al. [2017] Gathercole et al. [2015b]				Time required to perform the concentric CMJ phase.
Thorlund et al. [2008]	CMJ	Eccentric Acceleration Time (ms)	1	Interval between the start of downward movement (velocity increases negatively) and the instant of maximal negative velocity.
Thorlund et al. [2008]	CMJ	Eccentric Deceleration Time (ms)	1	Interval between maximal negative velocity (i.e. instant that force = body mass) and the time when velocity reached zero (i.e. the end of downward movement).
Thorlund et al. [2008]	CMJ	Eccentric Phase Time (s)	4	Total time of negative velocity prior to take-off.
Gathercole et al. [2015a] Kennedy et al. [2017] Gathercole et al. [2015b]				Time required to perform the eccentric CMJ phase.

Table 4.5. (Continued).

References	Test	Metric	N	Calculation
Gathercole et al. [2015b]	CMJ	Rate of Power Development (W/s)	1	Largest power increase during a 30 ms epoch.
Gathercole et al. [2015b]	CMJ	Mean Eccentric and Concentric Power Over Time (W/kg/s)	2	The sum of power produced during both eccentric and concentric CMJ phases, divided by the time taken (in ms) to perform the jump.
Kennedy et al. [2017]				
Gathercole et al. [2015a]	CMJ	Mean Eccentric and Concentric Power (W/kg/s)	1	The sum of power produced during both eccentric and concentric CMJ phases.
Thorlund et al. [2008]	CMJ	Relative Concentric Peak Power (W/kg)	1	Concentric peak power divided by body mass (kg).
Gathercole et al. [2015a]	CMJ	Relative Peak Power (W/kg)	1	Peak power divided by body mass (kg).
Boullosa et al. [2011]	CMJ	Peak Power (W/kg)	6	Greatest instantaneous power produced during the propulsion phase.
McLellan et al. [2012]				Peak force was multiplied by the peak velocity in the propulsive phase.
Gathercole et al. [2015a]				Greatest power achieved during the jump.
Kennedy et al. [2017]				
Gathercole et al. [2015b]				
Clarke et al. [2015]				Peak force multiplied by peak velocity.
Thorlund et al. [2008]	CMJ	Relative Concentric Mean Power (W/kg)	1	Concentric mean power divided by body mass (kg).
Gathercole et al. [2015a]	CMJ	Relative Mean Power (W/kg)	1	Mean power divided by body mass (kg).
Boullosa et al. [2011]	CMJ	Mean Power (W/kg)	4	Average power produced during the propulsion phase.
Gathercole et al. [2015a]				Mean power generated during the concentric phase of the jump.
Kennedy et al. [2017]				
Gathercole et al. [2015b]				
Thorlund et al. [2008]	CMJ	Relative Concentric Work (J/kg)	1	Not described.

Table 4.5. (Continued).

References	Test	Metric	N	Calculation
Thorlund et al. [2008]	CMJ	Velocity at Concentric Peak Power (m/s)	1	Not described.
Gathercole et al. [2015b]	CMJ	Velocity at Peak Power (m/s)	1	The velocity recorded at the time point where peak power occurs.
Gathercole et al. [2015a]	CMJ	Peak Velocity (m/s)	3	Greatest velocity achieved during the jump.
Kennedy et al. [2017]				
Gathercole et al. [2015b]				
Gathercole et al. [2015b]	CMJ	Minimum Velocity (m/s)	1	Lowest jump velocity during the eccentric phase.
Thorlund et al. [2008]	CMJ	Concentric Peak Velocity (m/s)	1	Not described.
Gathercole et al. [2015a]	CMJ	Area Under the Force-Velocity Trace (Ns)	3	The area under the force–velocity trace where eccentric movement is performed (ie, the area under the left side of the trace).
Kennedy et al. [2017]				
Gathercole et al. [2015b]				
Gathercole et al. [2015b]	CMJ	Relative Net Impulse (Ns/kg)	1	Total impulse divided by participant's body mass (kg).
Gathercole et al. [2015b]	CMJ	Total Impulse (Ns)	1	Force exerted concentrically multiplied by the time taken concentrically.
Boullosa et al. [2011]	CMJ	Vertical Stiffness (N/m/kg)	1	Not described.
Thorlund et al. [2008]	CMJ	Relative RFD 0–100 ms (N/s/kg)	1	Maximal vertical force achieved within 100 ms divided by 100 ms, divided by body mass.
Thorlund et al. [2008]	CMJ	Relative RFD 0–50 ms (N/s/kg)	1	Maximal vertical force achieved within 50 ms divided by 50 ms, divided by body mass.
McLellan et al. [2012]	CMJ	RFD (N/s)	2	The maximum force that occurred over the "first derivative" of the force-time curve.
Gathercole et al. [2015b]				Largest force increase during a 30 ms epoch.

Table 4.5. (Continued).

References	Test	Metric	N	Calculation
Thorlund et al. [2008]	CMJ	Relative Force at Concentric Peak Power (N/kg)	1	Not described.
Yu et al. [2020]	CMJ	Landing Peak Vertical Force (N)	1	Not described.
Gathercole et al. [2015a]	CMJ	Force at 0 Velocity (N)	3	The force exerted at the end of the countermovement where the jump transitions from eccentric to concentric movement (ie, velocity is at zero).
Kennedy et al. [2017]				
Gathercole et al. [2015b]				
Yu et al. [2020]	CMJ	Push-off Peak Vertical Force (N)	1	Not described.
Lupo et al. [2021]	CMJ	Peak Concentric Force (N)	2	Maximal vertical force during the concentric phase (between the instant that the center-of-mass velocity exceeded 0.01 m/s^{-1} and the instant of takeoff (ie, when the vertical ground reaction force fell below 5 times the SD of the flight phase force).
Thorlund et al. [2008]				Maximal vertical force during the concentric phase (when velocity was positive).
Gathercole et al. [2015a]	CMJ	Relative Peak Force (N/kg)	1	Peak force divided by body mass (kg).
Boullosa et al. [2011]	CMJ	Peak Force (N)	7	Greatest vertical force produced during the propulsion phase.
McLellan et al. [2012]				Maximum vertical ground reaction force achieved.
Gathercole et al. [2015a]				Greatest force achieved during the jump.
Kennedy et al. [2017]				
Gathercole et al. [2015b]				
Oliver et al. [2008]				Greatest force generated during the propulsion phase.
Clarke et al. [2015]				Maximum vertical ground reaction force achieved.
Thorlund et al. [2008]	CMJ	Relative Concentric Mean Force (N/kg)	1	Concentric peak force divided by body mass (kg).
Gathercole et al. [2015a]	CMJ	Relative Mean Force (N/kg)	1	Mean force divided by body mass (kg).
Gathercole et al. [2015a]	CMJ	Mean Force (N)	4	Mean force generated during the concentric phase of the jump.
Kennedy et al. [2017]				
Gathercole et al. [2015b]				
Oliver et al. [2008]				Mean force generated during the propulsion phase.
Oliver et al. [2008]	CMJ	Propulsive Force (N)	1	Not described.
Thorlund et al. [2008]	CMJ	Relative Eccentric Peak Force (N/kg)	1	Eccentric peak force divided by body mass (kg).
Oliver et al. [2008]	CMJ	Braking Force (N)	1	Not described.

Key: CMJ, countermovement jump; SD, standard deviation; TOV, take-off velocity; cm, centimetres; m, metres; s, seconds; N, Newtons; kg, kilograms; J, Joules; W, Watts; AU, Arbitrary Unit.

Table 4.6. Tally Illustrating Drop Jump Metric Selection and Calculation Methods.

References	Test	Metric	N	Calculation
Merrigan et al. [2021]	DJ	RSI (AU)	1	Flight time divided by contact time.
Merrigan et al. [2021]	DJ	Jump Height (cm)	1	Via the flight time method (1/2 gravitational acceleration * (flight time / 2)^2).
Oliver et al. [2008]	DJ	Flight Time (ms)	1	The time between when force was < 10 N (instant of take-off) and when force returned to < 10 N (instant of touch-down).
Horita et al. [1999]	DJ	Take-off Velocity (m/s)	1	Not described.
Horita et al. [1999]	DJ	Knee Positive Peak Power (W/kg)	1	Not described.
Merrigan et al. [2021]	DJ	Impulse (Ns)	1	Area under the force-time curve.
Horita et al. [1999]	DJ	Concentric Stiffness (N/m/kg)	1	Not described.
Horita et al. [1999]	DJ	Initial Stiffness (N/m/kg)	1	Not described.
Merrigan et al. [2021]	DJ	RFD (N/s)	1	Change in vertical ground reaction force from contact to 20 ms after contact divided by 20 ms.
Oliver et al. [2008]	DJ	Impact Force (N)	1	Not described.
Merrigan et al. [2021]	DJ	Peak Force (N)	2	Maximal vertical ground reaction force.
Oliver et al. [2008]				Not described.
Oliver et al. [2008]	DJ	Mean Force (N/kg)	1	Not described.
Oliver et al. [2008]	DJ	Propulsive Force (N)	1	Not described.
Oliver et al. [2008]	DJ	Braking Force (N)	1	Not described.
Merrigan et al. [2021]	DJ	Contact Time (ms)	2	Duration from contact (when forces were > 5 SDs above the one-second quite weighing phase average) to takeoff (when forces were < 5 SDs of the quite weighing phase).
Oliver et al. [2008]				The period between when force change by more than 10 N from resting body weight (initiation of movement), to when force was < 10 N (instant of take-off).

Key: DJ, drop jump; SD, standard deviation; cm, centimetres; m, metres; s, seconds; AU, arbitrary unit; N, Newtons; kg, kilograms; W, Watts; ms, milliseconds.

Table 4.7. Tally to Illustrate Squat Jump Metric Selection.

References	Test	Metric	N	Calculation
Oliver et al. [2008]	SJ	Flight Time (ms)	1	The time between when force was < 10 N (instant of take-off) and when force returned to < 10 N (instant of touch-down).
Oliver et al. [2008]	SJ	Peak Force (N)	1	Not described.
Oliver et al. [2008]	SJ	Mean Force (N)	1	Not described.
Oliver et al. [2008]	SJ	Propulsive Force (N)	1	Not described.
Oliver et al. [2008]	SJ	Contact Time (ms)	1	The period between when force change by more than 10 N from resting body weight (initiation of movement), to when force was < 10 N (instant of take-off).
Key: SJ, squat jump; N, Newtons; ms, milliseconds.				

Table 4.8. Tally Illustrating Unilateral Assessments Metric Selection and Calculation Methods.

References	Test	Metric	N	Calculation
Bromley et al. [2021]	Unilateral CMJ	Jump Height (m)	1	Jump height was calculated using the velocity at take-off. Dominant Leg Determination Not Described.
Bromley et al. [2021]	Unilateral CMJ	Landing Impulse (Ns)	1	The sum of impulse on landing up until peak landing force. Dominant Leg Determination Not Described.
Bromley et al. [2021]	Unilateral CMJ	Concentric Impulse (Ns)	1	The sum of impulse from the end of the braking phase up until take-off. Dominant Leg Determination Not Described.
Bromley et al. [2021]	Unilateral CMJ	Eccentric Impulse (Ns)	1	The sum of impulse from the end of unweighting period up until the end of the braking phase. Dominant Leg Determination Not Described.
Bromley et al. [2021]	Unilateral CMJ	Peak Landing Force (N)	1	Maximum force obtained during the landing phase of the jump. Dominant Leg Determination Not Described.
Bromley et al. [2021]	Unilateral CMJ	Peak Propulsive Force (N)	1	Maximum force obtained during the propulsive phase of the jump. Dominant Leg Determination Not Described.
McCall et al. [2015]	Isometric posterior lower-limb muscle test	Peak Force (N)	1	The maximum ground reaction force achieved. Dominant Leg Determination Not Described.

Table 4.8. (Continued).

References	Test	Metric	N	Calculation
Troester et al. [2019]	Unilateral Drop Landing	Time To Stabilisation (s)	1	The time required for force to equalise within 5% of baseline. Dominant Leg Determined as Kicking Leg.
Troester et al. [2019]	Unilateral Drop Landing	Sway Velocity (cm·s)	1	Total displacement of the centre of pressure divided by the duration of the trial. Dominant Leg Determined as Kicking Leg.
Troester et al. [2019]	Unilateral Drop Landing	Impulse (Ns)	1	Not described. Dominant Leg Determined as Kicking Leg.
Troester et al. [2019]	Unilateral Drop Landing	Peak Force (N)	1	Not described. Dominant Leg Determined as Kicking Leg.

Key: CMJ, countermovement jump; N, Newtons; m, metres; s, seconds; kg, kilograms; cm, centimetres.

4.5 DISCUSSION

The purpose of this scoping review was to identify and describe previous practices of monitoring acute changes in NMF using force plates. Following the application of the search criteria, 22 studies involving the acute monitoring of NMF using force plates were identified [43-49, 52-56, 65, 98, 116, 233, 239-244]. These 22 studies were qualitatively assessed to determine the characteristics of the studies methodologies. There was a prominent lack of consistency in study design, including subject characteristics, force plate hardware used, tests prescribed, metrics calculated from the force-time data (including data analysis procedures), metric terminology used, activity performed, and testing timepoints across studies monitoring acute changes in NMF using force plates. Only 16 of the 22 studies included sufficient results information of a point measure and measure of variability (e.g., mean and SD) for each measure at each timepoint [44, 45, 47-49, 52-55, 65, 98, 116, 233, 239, 240, 244]. Thus, only these 16 studies could be used to collate metric and study design information.

4.5.1 Hardware

To the author's knowledge, the results of this review are the first to illustrate the range of force plate manufacturers and models utilised in research for assessing acute changes in NMF (Table 4.3). Silva et al. [245] performed a scoping review aiming to map the methodologies used in research for analysing human movement among healthy adolescents. The review reported the use of kinetic data only once out of the 10 studies which met the inclusion criterion, which was conducted using force plates. This study was conducted by Pau et al. [246], who evaluated centre of pressure mean velocities during quiet standing in both the anteroposterior and mediolateral directions, at a sampling frequency of 33 Hz. Silva et al. [245] concluded that the lack of collection of kinetic data across these studies was likely to do with the feasibility of testing in a "real-world" environment [245]. In this review, a total of 14 different force plate models were reported across the 22 studies included in this review. The most common force plate manufacturer was Kistler Instruments Ltd (N = 8), with 6 different models reported, who are known for producing force plate models which utilise piezoelectric load cells, such as the model "92866aa" utilised in the study by West et al. [56] (Table 4.3). AMTI were also reported multiple times in this review (N = 3), who typically produce force plate models which utilise strain gauge load cells, such as the Model Biomechanics Measurement Series 400800 utilised by Scanlan et al. [239]. Strain-gauge load cells are also used in the 400 Series Performance Plate by Fitness Technology, which was the most frequently reported force plate model in this review (N = 5) [45, 65, 116, 242, 243].

The selection of a force plate system to test specific fitness qualities depends upon accessibility, feasibility, and affordability [247]. Traditional force plate systems (e.g., in-ground, laboratory-grade, wired systems) are restrictive in terms of location and manoeuvrability, and often fitted into University or School laboratories which require athletes to attend to collect data [246], but monitoring acute changes in NMF after training or match-play is a task tailored to real-world testing environments, and the information from these assessments is required immediately [247]. A recent study comparing a wireless (HD Inc. 3rd Generation, model 0484) vs in-ground, wired, laboratory based, "gold standard" (AMTI Model Biomechanics Measurement Series 400600) strain-gauge force plate system concluded that the wireless and portable HD Inc. system is as accurate as the less feasible, in-ground, "gold standard", AMTI force plate system, and thus can be considered as a more feasible option for real-world practice [21]. Additionally, the emergence of integrated proprietary software are much more feasible for real-world practice as they provide coaches with the ability to immediately and appropriately analyse, interpret, and act upon testing data could explain the more recent growing body of practice based force plate research [20]. Consequently, the emergence and validation of wireless force plate system (i.e., the HD Inc. system) hardware [21] and software [20] against traditional "gold standard" systems has enabled immediate automated feedback which is critical to physical practitioners [247], and confidence in system accuracy to overcome the issue of feasibility. This is positive for future practice and research looking to utilise an accurate yet feasible force plate system for monitoring acute changes in NMF in professional sports setting [21]. However, despite the HD Inc. system being a wireless system which has been validated against a traditional "gold standard" system in published research [21], it did not feature in any of the studies utilised in this review. This could be explained by the time of emergence of the HD Inc. system (circa 2016) in relation to the publication dates of the studies included in this review. Specifically, half of the included studies (N = 11) were published from 1999 to 2015 [44, 47, 49, 52-56, 65, 116, 242], and half (N = 11) were published from 2016 onwards [43, 45, 46, 48, 98, 233, 239-241, 243, 244], yet published research validating the HD Inc. system was not published until 2023 [21].

4.5.2 Data Collection Protocols

The standardisation and consistent implementation of force plate data collection protocols is critical to the fitness testing process to allow for accurate and reliable comparisons of data [247]. For example, specific force plate models are limited in their sampling frequency capability, therefore, an appropriate model must be chosen and consistently applied across testing sessions [247]. In this study, sampling frequency was one of the more well reported data collection protocols (N = 19 out of 22), however, a range of different data collection frequencies was utilised across studies (N = 7) (Table 4.3). A minimum sample frequency of 1000 Hz has been recommended for the collection of force plate data in VJ tasks [248, 249], which might explain why the most popular data collection frequency utilised was 1000 Hz (N = 10), with 5000 Hz (N = 1) and 200 Hz (N = 3) being the highest and lowest frequency reported, respectively (Table 4.3). Whilst the 400 Series Performance Plate by Fitness Technology was the most frequently reported force plate model in this review (N = 5), two different sampling frequencies were used in studies, which included 400 Hz [65, 116, 242] and 600 Hz [45, 243] to collect VJ force-time data, which are both lower than the recommended 1000 Hz [248, 249]. Additionally, the preferable surface used for force plate testing would be flat and solid (e.g., concrete) to prevent any unwanted deviations in raw GRF, that might occur due to unlevel force plates or cushioned flooring [247]. Despite this, only Troester et al. [240] reported detail regarding the surface used out of the 22 studies included in this review (Table 4.2). Similarly, there was a general lack of reporting of details of the footwear worn for testing (N = 4), which is concerning given that significant ($p < 0.05$) differences have been reported when running (6.7 $m \cdot s^{-1}$) in footwear with cushioned outsoles (i.e., “running shoes”) versus “flat sole racing shoes” in force plate metrics such as peak vertical impact force (2.36 ± 0.55 and 2.96 ± 0.67 N/bw, respectively) and peak braking force (-0.67 ± 0.14 and -0.88 ± 0.26 N/bw, respectively) in male NCAA Division I distance track athletes (age: 21.6 ± 3.0 years; height: 1.78 ± 0.05 m; mass: 66.3 ± 6 kg) [250].

Once the force plate testing system and placement is standardised, data collection protocols must also be appropriate and consistent across sessions. Familiarisation and warm-up protocols were reported in more than half the studies included in this review (N = 14, and N = 13, respectively) (Table 4.2). It is important that details of familiarisation and warm-up protocols are reported in literature to provide confidence that the presented data represents “maximal” NMF during trials. This is especially important in test-retest reliability studies, where familiarisation is advised prior to any force plate testing, because a lack of it in a specific task can result in inconsistencies between sessions [189]. Thus, it is recommended that details of familiarisation and warm-up protocols are provided in future studies. The zeroing of force plates between trials is also important, as a failure to do so over many trials can cause integration drift leading to erroneous data. Additionally, appropriate processes for weighing athletes during trials is critical, as fluctuations in body weight due to inconsistencies in weighing during VJ trials would compromise the reliability of metrics calculated via forward dynamics, specifically related to acceleration, velocity, and displacement [23]. For the most accurate and reliable data, these factors must be appropriately standardised and repeated between sessions, therefore, it is concerning that of the 22 studies included in this review, the processes of weighing athletes (N = 3) and the zeroing of force plates (N = 3) was scarcely reported (Table 4.2).

The standardisation of verbal instructions and trial technique is also vital to achieving accurate and reliable force-time data [247]. Jidovtseff et al. [184] reported that the verbal cues given to subjects affects the force-time characteristics, CM depth adopted, movement time performed, and the resultant outcome of VJ tasks. Most studies included in this review (N = 16) provided information regarding the utilised verbal cues, and the most common included "jump as high as possible" (N = 10) and perform trials to a "self-selected countermovement depth" (N = 12) (Table 4.2). Such a technique has been described to promote a more "compliant" strategy, characterised by applying impulse throughout a longer movement time to achieve greater TOV and JH [184]. It makes sense that technique to encourage greater JH has been applied most frequently given that JH was the most frequently reported measure for monitoring acute changes in NMF. However, a combination of ratio, outcome, strategy, and kinetic metrics might provide a better view of overall NMF [186], therefore, other verbal cues (e.g., "jump as fast and high as possible") could be more suitable. The standardisation of AS within- and between-sessions is also important because utilising an AS has been shown to augment JH [251], but has demonstrated slightly worse measurement reliability than VJs performed without, potentially owing to the increased potential for variation in technique [252]. All studies included in this review which provided details of AS standardisation reported an instruction to perform VJ trials with "hands-on-hips" (N = 10) (Table 4.2). Regardless of the approach prescribed, consistency in performed VJs with or without AS is required to avoid unwanted alterations in the force-time characteristic and outcome of VJ trials between subjects and sessions.

4.5.3 Study Design

To the author's knowledge, the results of this review are the first to illustrate the range of study designs in research concerning monitoring acute changes in NMF using force plates (Table 4.3). Most research on monitoring acute changes in NMF in sports populations (N = 19) occurred during the in-season period (N = 14) compared to the pre-season period (N = 1) in their respective sports, but several studies did not provide this information (N = 4) which is unfavourable in terms of research (Table 4.2). A portion (N = 6) of the monitoring in sports populations was conducted around a typical sports schedule, such as a competitive match (N = 3), a regular "field-based" training session (N = 2), and across a regular training week (consisting of multiple training sessions and a competitive match) (N = 1) (Table 4.4). These findings are understandable given that the rationale for monitoring acute changes in NMF during the competitive (i.e., in-season) period would be to aid in the planning of recovery and the optimisation of physical preparedness for competition, particularly in team sports [253] with congested fixture schedules (e.g., soccer) [72, 74, 110]. Overall, most (N = 10) monitoring was employed around standardised activity regimes, such as simulated match-play (N = 3), a HIIT training session (N = 2), or a laboratory-based, treadmill, incremental cardiovascular fitness test (N = 5) (Table 4.4). Although absolute physical output can be better controlled in these settings, the use of laboratory-based data collection procedures may not transfer to real-world settings [253], thus, it is encouraged that future research that aims to inform practice is competitive sports is performed in competitive sports scenarios and environments.

Quantifying measures of TL is useful as it provides objective information regarding athlete locomotion and an individual's physiological response to it [254]. External TL values were the most frequently utilised in research monitoring acute changes in NMF (N = 7). Similarly, Guthrie et al. [23] reported an abundance of studies (N = 11) evaluating longitudinal changes in physical preparedness which utilised external workload measures. The most common measures presented in the review by Guthrie et al. [23] were total distance covered (N = 2), "high-speed" (4.2 to 5.8 m/s) distance covered (n = 13), "very high-speed" (5.5 to 6.4 m/s) distance covered (n = 2), and "sprint" (>6.7 m/s) distance covered (N = 1), whilst one article quantified external workload as total competitive match minutes [23]. This review identified that total distance covered (m) was the most frequently utilised in research monitoring acute changes in NMF (N = 4). External workload data is often accompanied by internal workload (sometimes referred to as "intensity") data, which is commonly measured through players wearing devices which monitor changes in HR [98]. A combination of external and internal workload measures should be used as an indicator of overall TL, because an individual's physiological response to the external workload performed during training and matches can differ between athletes [98]. The findings of this study mirror exactly the findings of Guthrie et al. [23], where internal workload measures were utilised less frequently (N = 2) than external workloads, and solely assessed via HR measures, with average [53] and maximum [55] HR utilised once in separate studies.

Potentially the most important factor in monitoring acute changes in NMF is determining the testing time-points to be employed. Fatigue mechanisms work in different combinations, magnitudes, and timeframes throughout competition and during the recovery process [106]. For example, towards the end of and immediately after a competitive soccer match, neuromuscular fatigue is present due to the confounding impacts of mechanical processes (e.g., muscle damage), bioenergetic processes (e.g., lowered muscle glycogen), metabolic processes (e.g., lactate accumulation and acidity), and their effect on neural processes (e.g., disturbances in muscle ion homeostasis and an impaired excitation of the sarcolemma) [95, 103, 106]. Of the various baseline testing timepoints reported in this review (N = 6), immediately (<15 min) prior to activity was the most frequent (N = 13) (Table 4.4). A greater variation of testing timepoints post-activity was seen (N = 12), but immediately (<15 min) post-activity was also prescribed most frequently (N = 11) (Table 4.4). These findings are understandable given that testers would wish to mitigate any confounding factors in-between testing and the activity of interest which could affect the true determination of neuromuscular fatigue in response to a specific activity. Once an athlete returns to training (usually within 72 hours post-match) [19], the accumulation of mechanical, neural, bioenergetic, and metabolic fatigue would likely create a DTE, DOMS, and resultant impairment of physical capacity [19]. This might explain why, second to immediately post-activity testing, the most common testing timepoints reported were +24 h (N = 5), +48 hours (N = 3), and +72 h (N = 3), which as stated, might represent when athletes return to training and the days following that in these studies, where the monitoring of recovery and adaptation are warranted (e.g., before players commence preparations for the next match). Understanding that an impairment in NMF at different testing timepoints is due to differing physiological factors can help practitioners to prescribe appropriate recovery strategies.

4.5.4 Tests

In various sports, dynamic force plate tests are employed as an objective measure of a specific task performed in competition (e.g., jumping to perform a block in basketball), or as an indicator of lower-body NMF which relates to other sports specific tasks (e.g., in sprinting and changing direction) [247]. When determining a suitable dynamic test, it should be considered if tests are to be performed unilaterally or bilaterally, with or without a countermovement, and vertically or horizontally [247]. Guthrie et al. [23] illustrated that dynamic tests (N = 14) were more popular than isometric tests (n = 2) in research evaluating longitudinal changes in physical preparedness. Of these dynamic tests, all were vertically orientated (i.e., VJ tests), where the bilateral CMJ was the most frequently utilised (N = 11), followed by the bilateral SJ (n = 2), and the unilateral CMJ test (N = 1) [23]. The results of the present review demonstrate many similarities to those of Guthrie et al. [23], with a proportionally greater use of dynamic assessments (N = 22) compared to isometric assessments (N = 2) in research monitoring acute changes in NMF (Table 4.2). Of these dynamic assessments, all were also vertically orientated (i.e., VJ tests), and the majority (N = 20) were bilateral in nature, where unilateral dynamic assessments featured to a lesser extent (N = 2) (Table 4.2). The same as the findings of Guthrie et al. [23], the most popular VJ assessments identified in this review were performed with a countermovement, including the slow SSC (i.e., "ballistic") CMJ test (N = 16), followed by the fast SSC (i.e., "plyometric") DJ test (N = 3), whilst the concentric-only SJ test was reported only once (Table 4.2).

Guthrie et al. [23] considered that the popularity of utilisation of the bilateral and vertically orientated CMJ test as an indicator of ballistic lower-body NMF might be due to its ease of application, as it requires minimal familiarity, skill, equipment, and time to complete the test, as well as having a low mechanical and metabolic demand (and thus fatigue and risk of injury). This makes the CMJ test well suited to testing both beginner and more advanced individuals and groups of athletes with ease [247]. Along with this feasibility, a plethora of temporal phase kinetic and kinematic metrics can be calculated from a CMJ force-time curve to provide a detailed overview of lower-body NMF [25]. Isometric tests offer an alternative option to dynamic tests which also demonstrate high feasibility and low mechanical and metabolic demand, which also makes them well suited to testing both beginner and more advanced athletes [247]. However, conducting isometric tests often requires specific equipment configurations (e.g., a custom made IMTP or isometric squat rig) [241], and many tests are performed unilaterally [47], thus often making data collection more complicated, lengthy, and less favourable for practitioners working with large groups of athletes. This could explain why the frequency of utilisation of isometric assessments in research monitoring acute changes in NMF was minimal (N = 2) (Table 4.2), where tests such as the "isometric posterior lower-limb muscle" [47] and "isometric squat" [241] featured only once in separate studies (Table 4.2). These findings mirror those of Guthrie et al. [23], who also reported only two studies which utilised isometric assessments (both utilising the IMTP test), compared to 14 studies which utilised dynamic tests to evaluate long-term changes in physical preparedness following training programmes [23].

4.5.5 Metrics

The results of this review have identified an abundance of metrics (N = 87) across various tests that have been calculated from force-time data to inform practitioners of acute changes in NMF (Tables 4.5-4.9). Out of the metrics reported in these studies, the greatest variety was seen in CMJ metrics (N = 52), where combinations of outcome (N = 2; 3.8%), force (N = 20; 38.5%), work and power (N = 10; 19.2%), velocity (N = 5; 9.6%), and strategy (N = 15; 28.8%) metrics were used to monitor acute changes in NMF (Table 4.5). Despite CMJ outcome measures showing the least variety, JH was the most frequently reported of all metrics (N = 7) (Table 4.5), which corresponds with the findings of Guthrie et al. [23] who reported JH was the most frequently utilised metric used as an indicator of changes in physical preparedness longitudinally (N = 9) [23]. A benefit to utilising force plate systems to monitor NMF is they offer the potential to calculate a vast range of metric types, including ratio, outcome, strategy, and kinetic metrics [186]. This permits a more extensive assessment of NMF by allowing practitioners to identify more than solely outcome measures (e.g., JH), which may offer limited utility for detecting neuromuscular fatigue [255], because changes in kinetic output can alter jump strategy alongside a maintenance in JH [186]. For example, monitoring JH alone might indicate a maintenance of NMF (i.e., minimal neuromuscular fatigue) following activity, which could be misleading if other kinetic and strategy metrics change concurrently [186].

This review identified a range of CMJ kinetic measures utilised in research monitoring acute changes in NMF, such as peak (N = 7) and mean (N = 4) force, peak (N = 6) and mean (N = 4) power, and peak velocity (N = 3). This is a greater variety of metrics in comparison to findings of Guthrie et al. [23] who, despite showing commonality in the frequent use of peak power (N = 3) across studies evaluating longitudinal changes in physical preparedness, the only other kinetic measure reported was “relative power”, which featured only once out of thirty-one studies included within the review [23]. The review by Guthrie et al. [23] also did not identify the use of any strategy metrics, whilst the current review identified a variety of them, including eccentric (N = 4) and concentric (N = 4) phase time, and total movement time (N = 3), which are important to consider when evaluating NMF using dynamic tasks given that the strategy of a VJ directly impacts its outcome (i.e., JH) [184]. The only CMJ ratio metric identified within this review and the review of Guthrie et al. [23] was the FT:CT ratio, which was utilised only twice in both reviews. Despite metric popularity, in order for the chosen force plate metrics to be useful they must first be meaningful in that they are associated to independent measures of performance in the subject’s sport or occupation (e.g., strength, linear speed, and COD ability)

[115]. Accordingly, CMJ metrics such as JH, peak force, and peak power have been related to independent "field-based" measures of strength and speed [115]. Given the importance of strength and speed for many athlete populations, it seems that a strong basis exists for including metrics such as JH, peak or mean force, and peak power, during CMJ testing [115]. Additionally, although specific metrics might be determined as meaningful in that they are strongly associated with independent physical performance measures, a metric's reliability will ultimately determine its ability to detect acute changes in NMF [205]. Consequently, the test-retest reliability of these frequently reported ratio, outcome, strategy, and kinetic metrics should be determined before appropriate practical conclusions can be constructed.

Whilst a variety of DJ metrics were identified in this review (N = 15), there was a lack of uniformity in metric selection with only peak force (N = 2) and contact time (N = 2) being reported more than once (Table 4.6). Because fast SSC tasks must be performed with a GCT of less than 250 ms to be considered truly "plyometric" [117], it seems reasonable that contact time would be a popular metric for articles utilising this test. To meet this requirement, fast SSC tests are required to be performed with a "stiff" strategy [184]. This typically results in greater peak forces than similar tests performed with a more complaint strategy (e.g., depth jumps) [184], which is also why it is understandable that peak force was a commonly reported DJ metric (Table 4.6). Additionally, because of this focus on the standardisation of contact time in fast SSC tasks, and the frequent use of JH as an indicator of VJ performance [23], ratio metrics such as the RSI have been proposed in literature as a metric which indicates how "fast and high" a fast SSC test is performed [229]. If monitoring multiple metrics concurrently to determine changes in NMF, it might be common to find a scenario where one metric changes but another does not [115]. In this instance, it seems challenging to determine whether overall NMF has truly gotten better, worse, or not changed [115]. Bishop et al. [186] suggested that practitioners may wish to consider 'linking metrics together' (e.g., utilise ratio metrics) when interpreting data from VJ testing, as a way to utilise separate aspects of useful information concurrently [115]. It seems logical to assume that combining information about said metrics to form ratio metrics would streamline the monitoring process, but the individual components of any ratio metric also need to be considered to provide context to change. The use of RSI has been reported in research evaluating longitudinal developments in NMF [23], but this was not a metric utilised in research monitoring acute changes in NMF (Table 4.6). Future research on monitoring acute changes in NMF should determine the utility of ratio metrics for this purpose.

Furthermore, where a lack of research was identified utilising the concentric-only (i.e., the SJ), unilateral and isometric assessments, all associated metrics also only featured once (Tables 4.7-4.8). This gap in research is especially noticeable in the single study within this review which reported the use an isometric assessment (i.e., the "isometric posterior lower-limb muscle test") [47], where only peak force was the metric of interest (Table 4.8). This was also seen in the articles included in the review of Guthrie et al. [23], who reported the use of only peak force and RFD during the IMTP test, but this is understandable as these tests are typically employed to measure neuromuscular "strength" [256]. Future research should look to explore concentric-only, unilateral, and isometric assessments to discover their utility for monitoring acute changes in NMF. If performed with appropriate data collection and analysis methodologies, the information from studies can be accumulated for meta-analyses to inform future practice.

4.5.6 Data Analysis Procedures

This review has identified a lack of reporting of data analysis procedures across studies on monitoring acute changes in NMF, specifically, failing to provide calculations for CMJ (N = 11 out of 52; 21.2%), DJ (N = 9 out of 15; 60%), SJ (N = 3 out of 5; 60%), and unilateral test (N = 4 out of 14; 28.6%) metrics (Tables 4.5 to 4.8). Without the context of how metrics were calculated, data cannot be accurately compared across studies. For example, the calculation of CMJ JH varied most out of any metric reported across studies (N = 4), such as via TOV ($TOV^2 / 2 * g$) [52], peak velocity [65, 116, 233], FT (via $1/2\ g * [FT / 2]^2$ [239], and, $[g^{-2} * FT^2] / 8$ [244]), and as the height of the COM at the apex minus at the point of take-off [44]. It is recommended, particularly when utilising force plates which apply forward dynamics procedures and follow guidelines of the impulse-momentum theorem to determine TOV [15], that JH should be determined via the TOV method [230]. For comparison, utilising peak velocity would inflate JH as this occurs prior to the instant of take-off (i.e., prior to plantar flexion). Thus, it is concerning that the TOV method was only utilised once out of the 7 studies which reported CMJ JH (Table 4.5). Future research should accurately describe their metric calculations to allow for future comparisons and meta-analyses of data to inform future practice.

Varying calculations were also identified for kinetic measures such as peak force (N = 2), namely as either the maximum force achieved throughout the entirety of the CMJ trial [44, 49, 55, 65, 116, 233], or as the maximum force achieved during the propulsion phase [53]. This is a distinct difference, as the maximum force achieved during a CMJ can occur during the braking phase, prior to the initiation of the propulsion phase [25]. Thus, comparing "peak force” calculated in these separate ways would not be correct, where the latter would rather be best defined as “peak propulsive force” [25]. Peak concentric force was also reported and calculated as the maximal vertical force during the concentric phase in two separate studies [52, 98]. Although this metric calculation better fits the metric description, and was consistent across the studies reporting it [52, 98], this metric calculation matched that reported for peak force in the study by Oliver et al. [53] (greatest force generated during the propulsion phase). Differing phase terminology creates an issue for data comparison (e.g., via meta-analysis) and for interpretation of information from studies for use in practice. In this review, varying phase terminology, such as braking (N = 2), eccentric (N = 8), propulsive (N = 4), and concentric (N = 14) was identified across all studies (Tables 4.5 to 4.8). Like the differences presented above, CMJ phase terminology such as eccentric phase time [65, 116, 233] and concentric phase time [65, 116, 233] have been utilised, and mean force has been calculated as the mean force generated during the concentric phase of the jump [65, 116, 233] and the mean force generated during the propulsion phase [53], in separate studies. Future research should focus on standardising phase terminology for force plate tests to allow for future comparisons and meta-analyses of data to inform future practice.

Merrigan et al. [20] identified that the braking and propulsion phases of a CMJ test (as defined in HD Inc. proprietary software) have been incorrectly described as the eccentric and concentric phases, respectively, in separate commercially available force plate software, and the braking phase has been referred to as the eccentric phase in other published research [26-28]. This is potentially based on the assumption that the leg extensor muscles are actively lengthening (i.e., working eccentrically) to decelerate the body’s COM during this phase [25]. However, the collection and analysis of vertical force-time data using force plates only provides insight into the kinetics and kinematics of linear COM motion and cannot inform us as to what is occurring at the joint or MTU level [25]. Additionally, it is not only the leg extensors that contribute to the CMJ test, and it would be incorrect to assume that all lower-body MTUs are working eccentrically during the braking phase (e.g., the medial gastrocnemius may shorten during this phase [29]). These issues were also raised by Hahn [257] in a letter to the editor, who proposed the use of mechanical CMJ phase definitions such as unweighting, braking, and propulsion phases, determined via vertical COM velocity, in future research. However, Hahn [257] did not highlight the incorrect assumptions related to phase descriptions based on whether fascicles were actively lengthening (i.e., eccentric) or shortening (i.e., concentric) during these actions. Thus, as proposed in the work of McMahon et al. [25], the phase in VJ tasks which are calculated as when the instant of peak negative COM velocity until when COM velocity increases to zero (which coincides with the peak negative COM displacement), and from when a positive COM velocity is achieved until the instant of take-off, should be described as the "braking" and "propulsion" phases, respectively, and not the "eccentric" and "concentric" phases, respectively.

It is also evident from the results of this review that not only have the same metric terminologies been utilised with differing metric calculations, but the same calculations have been prescribed to differing metric terminologies in research monitoring acute changes in NMF (Tables 4.5 to 4.8). In combination with the described differing use of phase terminology, this makes the comparison of study data extremely difficult and unlikely. Such a difference was also identified for CMJ total movement time and take-off phase time, which were calculated as the time required to perform both the eccentric and concentric phase in separate studies (Table 4.5). These issues also extended to the calculation of power metrics such as CMJ peak power, where multiple calculations were reported (N = 4) across the 6 studies which utilised the metric (Table 4.5). These calculations included the greatest instantaneous power produced during the propulsion phase [44], peak force multiplied by peak velocity in the propulsive phase [49], the peak power achieved throughout the entirety of the CMJ trial [65, 116, 233], and peak force multiplied by peak velocity [55]. This again highlights distinct differences between the determination of a peak value throughout the entirety of a trial vs specifically during the propulsive phase.

For the remainder of test metrics identified in this study, only the DJ test demonstrated more than one metric calculation difference (Table 4.6). Specifically, contact time was calculated as the duration from contact (when forces were > 5 SDs above the one-second quite weighing phase average) to take-off (when forces were < 5 SDs of the quite weighing phase) [48], and the period between when force change by more than 10 N from resting body weight (initiation of movement), to when force was < 10 N (instant of take-off) [53], in separate studies. This example highlights a difference in phase identification, specifically in the determination of the instant of take-off and touchdown utilising standardised force thresholds (i.e., 10 N) [53] vs based on utilising 5 SDs of FT force [48] as recommended by McMahon et al. [25]. This is an issue as a difference in phase identification can affect the calculation of temporal aspects (e.g., contact time) and ratio metrics which include temporal measures within their calculations (e.g., RSI). Additionally, caution must be taken when determining the instant of touch-down and take-off utilising a specific force threshold as residual noise in the system can exceed 10 N dependent on the surface used, thus, understanding the phase thresholds utilised is important for the accurate determination of phase specific metrics when comparing data [25]. The authors refer readers to the work of McMahon et al. [25] for the accurate determination of CMJ phases.

4.6 CONCLUSIONS

Practitioners must apply monitoring strategies to manage neuromuscular fatigue and physical preparedness with valid, reliable, and sensitive measures [23]. The results of this review give an overview of the previously used methodologies for monitoring acute changes in NMF using force plates, and aimed to highlight issues and gaps that can be explored in future research. Major differences were identified across all aspects of studies methodologies, such as in subject demographics (e.g., sex, sport, and competitive level), data collection protocols (e.g., force plate hardware utilised, test and metric selection, verbal cues, and provision of information regarding testing surface, familiarisation and warm-up provided, the process of zeroing force plates between trials, and weighing of subjects during trials), and study design (e.g., reference physical activity investigated, time of season, testing timepoints, and TL determination). Additionally, the general lack of reporting and uniformity in metric definitions, metric calculations, and phase terminology across studies means an accurate comparison of results across studies (e.g., via meta-analysis) may not be possible, and any kind of generalized conclusions about the application of specific tests and metrics for monitoring acute changes in NMF using force plates would be premature at this time. With the recent growth in the utilisation of force plate measurements in real-world settings [160, 161], the production of research centred on developing and promoting standardised testing procedures to determine capable tests and metrics for the acute monitoring of changes in NMF using force plates seems like a logical suggestion for future investigations.

Research is required to be employed with appropriate and standardised study designs across various sports populations, where research determining metrics' sensitivity to change should be conducted in real-world environments where the information will be applied, for example, in team-sports (e.g., soccer) this could be applied around competitive matches (e.g., within 15 minutes pre- and post- an in-season competitive match), whilst reporting context of TL determination, if the intended data is to inform recovery processes. Additionally, it is important that studies report details of data collection procedures, such the surface used, footwear worn, warm-up and familiarisation protocols, process of zeroing force plates between trials, method of weighing participants during trials, and prescribed verbal cues to allow for replication and provide readers with confidence in the study's results. The determination of the reliability and sensitivity to change of various popular tests (e.g., CMJ, DJ, etc.) and range of metric types, including ratio, outcome, strategy, and kinetic metrics [186] is required to develop a suitable and well-informed best practice methodology. Finally, it is non-negotiable that future research should be conducted with appropriate data analysis procedures (i.e., correct metric terminology, calculations, phase identifications, and phase terminology) and report these procedures clearly in their methods sections. A validated approach is available via the HD Inc. force plate system's proprietary software, as reported by Merrigan et al. [20]. These aspects will allow for the comparison of results in future research (e.g., via meta-analysis), for a better translation of knowledge into practice [245], and ultimately, allow the monitoring of acute changes in NMF to be adequately applied in practice.

5 GENERAL METHODS

This section encompasses all the general methods that will feature throughout this thesis, and data analysis performed in the HD Inc. proprietary software. This chapter was written to ensure that a replication of methods descriptions does not occur throughout the methods sections of each chapter of this thesis. Only the parts unique to each chapter will be explained within the methods section of that chapter. For example, the data analysis for the validity study was performed separately and not via the HD Inc. proprietary software, and thus is described in full detail within that chapter.

5.1 GENERAL POINTS

5.1.1 Procedures

All testing sessions were preceded by a brief (~10 min) general warm-up consisting of dynamic raise, activation, and mobilisation exercises (i.e., linear jogging and bodyweight squats and lunges) and a specific warm-up and familiarisation consisting of submaximal efforts immediately prior to maximal effort trials of each test. This consisted of a single submaximal effort prior to each VJ test, and 2 warm-up trials at 50% and 75% of each athlete's perceived level of maximal effort prior to the IMTP test. All tests were performed in a randomised order. The first test's recorded trials (e.g., CMJs, DJ, CMRJ, or IMTP) were performed approximately three minutes following the completion of the warm-up and ~ one minute of rest was allocated between every recorded trial. Approximately three minutes followed the completion of a test (e.g., CMJ) until the commencement of the submaximal practice trial and maximal trials of the next test (e.g., CMRJ).

Participants performed all VJ trials with arms akimbo and were instructed to jump "as fast and high as possible". Researchers have reported that manipulating verbal instructions such as "jump as high as possible" (i.e., compliant strategy) vs "jump as fast as possible" (i.e., stiff strategy) produces markedly different force-time characteristics in the CMJ and DJ tests [184]. For example, greater net propulsive impulse involving lower peak force achieved over a greater propulsive phase time via the former instruction, and lesser net propulsive impulse involving greater peak force achieved over a shorter propulsive phase time via the latter instruction [184]. Thus, this combination of instructions is prescribed to neutralise the possibility that separate athletes will favour a compliant or stiff strategy separately, to ensure a comparison of scores is accurate.

If any of the three recorded maximal effort trials were not performed according to the defined technical criteria, they were omitted at the tester's discretion, based on their own visual observations from watching the participant perform trials and checking the tablet's immediate feedback. Up to an additional 2 trials (maximum 5 trials total) were performed in this instance after the standardised allocated rest period to allow for the collection of three trials performed to standard. Some examples of technical faults during testing include:

- AS performed during VJ trials [59] (assessed visually).
- Leg tucking during the flight phase of VJ trials [59] (assessed visually).
- Failing to land back on the force plates during VJ trials (assessed visually).
- Not achieving a GCT of <250 ms in the DJ and RJ portion of the CMRJ test (assessed via tablet's immediate feedback).
- A countermovement was performed during IMTP trials [187], etc. (assessed via tablet's immediate feedback).

Additional trials were also conducted if subjects' JH changed by ± 2 cm between VJ trials, or if peak force changed by ± 250 N between IMTP trials [187].

5.1.2 Data Collection

The vertical component of GRF data was collected using a wireless and portable dual force plate system, by HD Inc. (Westbrook, Maine, USA), at 1000 Hz. Filtering or smoothing techniques are often applied to force plate-derived vertical GRF data to make it less choppy, smoother, "cleaner", and thus easier to analyse [258]. However, it is recommended that a filtering technique is chosen based on the most appropriate method which accurately isolates the force-time signal without sacrificing data accuracy [258]. Many force plate systems have filtering and smoothing methods integrated into the proprietary software, which are typically programmed to be automatically utilised during the amplification process [258]. Yet, various filtering options are available to force plate users, including high-, low, and band-pass, notch, and stop-band [258]. Specifically, low- and high-pass filters eliminate frequencies in the force-time signal above and below a certain cut-off frequency, respectively [258]. In comparison to raw vertical GRF data, a low-pass filter with a 50-Hz cutoff frequency has been proven to remove data noise without altering biomechanical variables in a CMJ test [259]. Additionally, Butterworth filter methods, which operate sequentially through force-time data to correct phase-shift, have been considered well-suited for biomechanical variables [258]. As such, all data collected with the HD Inc. force plate system throughout this thesis were filtered using a low-pass Butterworth filter with a cut-off frequency of 50 Hz, as directed by HD Inc. and integrated into their proprietary software as it is considered a common and appropriate method for biomechanical variables in literature [258, 259]. HD Inc. proprietary software was downloaded onto the "Android" mobile operating system of Samsung "Galaxy Tab A7 Lite LTE" and Lenovo "Tab M10 Gen 3" tablets. The tablets were connected to the force plate via Wi-Fi Direct. For testing sessions involving multiple tests, a separate force plate system was used for each test to allow for the collection of test data simultaneously and make testing time efficient in a squad setting. However, the same system was used for the same test on each testing occasion.

In different locations, it was pre-arranged and prioritised that trials were conducted on solid, even, non-slip flooring to allow for the accurate collection of force-time data. Zeroing of the force plates was performed between trials. As the base plate of the force plate system has a height of 7 cm from the floor (Figure 5.1), all VJ tests were performed with a HD Inc. fit-to-size foam surround placed around the force plates to provide the participants with additional safety. It also served as a platform to allow for a box to be set-up at a level height with the force plates for DJ assessments. The foam surround was not applied to IMTP testing as it was not required for safety purposes. An image of the set-up of each respective test are provided in figures 5.2 (CMJ and CMRJ), 5.6 (DJ), and 5.7A and B (IMTP).

If trials successfully meet the specific test criteria, all data received by the tablet's proprietary software is presented on-screen to provide immediate feedback of the test results. During the collection of acceptable trials for each test, it was important to only feedback information to the athletes regarding if a trial was successful or not, and only providing coaching cues were necessary if a trial was performed undesirably (e.g., cueing an athlete to perform a DJ "more quickly" if a trial was performed without a GCT of <250 ms). This is due to the anecdotal observation that the feedback of performance via specific metrics often affected the strategy adopted during subsequent trials. For example, if the JH performed during each trial was highlighted on the tablet screen post-trials, athletes would generally focus on only achieving a greater JH and change their strategy to adopt a more compliant strategy. This consisted of a deeper countermovement depth and longer time to take-off, resulting in a greater net propulsive impulse, TOV, and thus JH [184]. This was an issue during data collection because athletes were cued to jump "as fast and high as possible", where metrics such as mRSI might be more applicable to feedback if a coach were to feedback any information at all. It has been determined in previous research that the cues provided to athletes during CMJ testing affects kinetic and kinematic performance [184]. However, as wireless force plate systems with proprietary software which provide automated feedback of test results are a relatively new addition to the applied setting, researchers could study this anecdote further by investigating the difference between feeding back individual test results using specific ratio (e.g., mRSI), outcome (e.g., JH), strategy (e.g., time to take-off), or kinetic (e.g., mean propulsive force) on VJ task execution.

After trial completion, users have the option to "save" or "discard" successful trials at their own discretion based upon the defined criteria. Saved trials are firstly stored locally on the tablet's proprietary software. If the testing location supports Wi-Fi, and the tablet is connected to the internet via Wi-Fi, this data will be automatically uploaded via "cloud computing" to the HD Inc. "cloud platform" (i.e., "the Hawkin Cloud"). The tablet must be connected to the internet for data to be transferred to the Hawkin Cloud as testing is being conducted. If the location does not support Wi-Fi, saved trials will remain saved on the tablet's proprietary software, ready to be batch uploaded to the Hawkin Cloud once the tablet next connects to the internet. The saved force-time data can then be accessed immediately in the Hawkin Cloud (https://cloud.hawkindynamics.com) where the data can be utilised as appropriate. This includes generating squad and individual reports (e.g., profiling, comparisons, and fatigue monitoring), exporting the testing session data in CSV format to be analysed in external software (e.g., Microsoft Excel, Google Sheets, and Numbers, etc.), for statistical analysis, or as "text files" of raw force-time data for individual trials for alternative data analysis.

Figure 5.1. Example force plate system set-up without the foam surround.

5.1.3 Data Analysis

Data analysis was automatically performed after each trial via the HD Inc. proprietary software. In the CMJ, DJ, and CMRJ tests, forward dynamics is applied to the force-time record to calculate a multitude of performance variables relating to acceleration, velocity, and displacement [25]. Specifically [25]:

The net force-time record is calculated by subtracting system weight from the vertical GRF-time record:

$$\text{Net vertical GRF} = \text{vertical GRF} - \text{body weight}$$

The acceleration-time record is calculated by rearranging Newton's Second Law of Motion, by dividing the net force-time record by the athlete's body mass:

$$\text{Acceleration} = \text{net vertical GRF} / \text{body mass}$$

The velocity-time record is calculated by numerically integrating the acceleration-time record with respect to time using the trapezoid rule. Displacement is calculated by numerically integrating the velocity-time record with respect to time using the trapezoid rule. Onset thresholds, phase descriptions, and metric definitions are presented in Tables 5.1-5.3.

5.2 COUNTERMOVEMENT JUMP

5.2.1 Data Collection

An image of the starting position for the CMJ test is provided in Figure 5.2. Participants stepped onto the force plates and stood completely upright (extended hips and knees) and motionless for at least one second of data collection to enable the subsequent determination of body weight, as described in Table 5.1. It is crucial that COM velocity and displacement are equal to zero at the onset of movement for numerical integration to be accurate. Participants were instructed to perform a CMJ trial by a “flash and beep” command on the tablet, which would not occur unless the conditions for the determination of bodyweight were met. Vertical GRF data was collected over five seconds, at 1000 Hz (low-pass Butterworth filtered with a cut-off frequency of 50 Hz applied by the proprietary software).

Figure 5.2. Starting Position of the Countermovement Jump Test.

5.2.2 Data Analysis

Through detailed analyses of CMJ force-time curves, researchers have identified six constituent parts of the CMJ test which can provide a more detailed illustration of NMF, rather than only considering the outcome (e.g., JH or TOV) alone [25]. The proposed six key "phases" of the CMJ test are termed the weighing, unweighting, braking, propulsion, flight, and landing phases [25]. The accurate determination of these six key phases of the CMJ test is essential for the correct calculation and representation of phase-specific variables, which will be outlined in this chapter. As an example, these include the correct determination of body weight, the force and velocity thresholds used to determine the start and end of each phase, and the sufficient sampling and numerical integration frequency applied during data collection [25].

5.2.2.1 Phase Descriptions

A small error in the measurement of bodyweight will translate into large errors in the estimation of JH [249]. Specifically, Street et al. [249] reported that an average increase of 0.25% across 22 subjects' bodyweights resulted in an average 6.5% underestimation of JH ($p < 0.0026$). Owen et al. [248] produced a criterion protocol for the measurement of lower body NMF via CMJ testing using force plates, recommending that bodyweight be determined as the average of vGRF during 1 s of data collection during the weighing phase. These recommendations stemmed from findings of Street et al. [249] who reported that weighing durations of ≥1 s resulted in only a ≤1% difference in JH (which is considered acceptable [25]) when compared to a weighing duration of 2 s [248]. For comparison, an error of 0.13% in bodyweight was reported when bodyweight was calculated via averaging vGRF over the first 0.1 s, which led to a ±3.3% difference in the estimation of JH [249]. Consequently, in the HD Inc. software, the weighing phase is determined as from the instant the trial is initiated (i.e., the moment the tester starts the test on the tablet) to the instant that the SD of vertical GRF is less than 25 N for ≥ 1 s [248, 249, 260]. In practice, the HD Inc. proprietary software ensures that weighing phase continues and the onset of movement is not initiated until this criterion is met. Thus, in addition to applying the recommendations of Owen et al. [248], a standardised threshold of 25 N (2.55 kg) ensures that the 1 s average of vGRF during the weighing period is not highly variable, providing further confidence in the accurate calculation of bodyweight. An explanation for the chosen 25 N threshold is not provided in the HD Inc. metric database [260] or information packet [261].

During this period, the participant is required to stand upright and as still as possible, until the initiation of the countermovement (i.e., unweighting phase) [260]. System weight (i.e., body weight) is calculated as the lowest 1 s average of the vertical GRF applied to the system COM, which is identified via an optimization loop [25, 260]. Body mass is determined as body weight divided by g which is selected as 9.81 m/s^2 [260]. The accurate calculation of body weight is essential for to identifying a threshold to determine the onset of movement, and because the body mass derived from it is included in calculations of the forward dynamics procedure [25]. Once the conditions of the weighing phase are met, the tablet provided a "flash and beep" command to instruct participants to initiate movement and begin the countermovement (i.e., initiation of the unweighting phase of the CMJ) [260]. During the unweighting phase, the participant will commence a countermovement by first relaxing the agonist muscles, resulting in a synchronised "passive" flexion of the hips, knees, and ankles to lower the body's COM [260]. As recommended in previous research [248], the onset of movement threshold is set at ± 5 SD of BW [260]. Therefore, the start of the unweighting phase (i.e., the onset of movement) is determined as the instant that vertical GRF exceeds 5 SDs above or below the system weight calculated during the weighing phase [260]. The start of numerical integration of a CMJ test trial using the HD Inc. system is determined via a backwards search of 200 ms (using the previously mentioned optimization loop) from the initiation of movement threshold to the closest value of system weight, using the methods of the trapezoidal rule [25, 260]. The end of the unweighting phase is determined as the frame before the instant of peak negative COM velocity [260], which is also equal to the instant that vertical GRF returns to body weight (Figure 5.3A) [25, 262]. This can be understood via Newton's second law (force = mass multiplied by acceleration) where because vertical GRF is equal to bodyweight the athlete has stopped accelerating downward and thus has reached their peak negative COM velocity [260]. Thus, the unweighting phase is the entire area of the force-time curve that is below bodyweight prior to take-off [25].

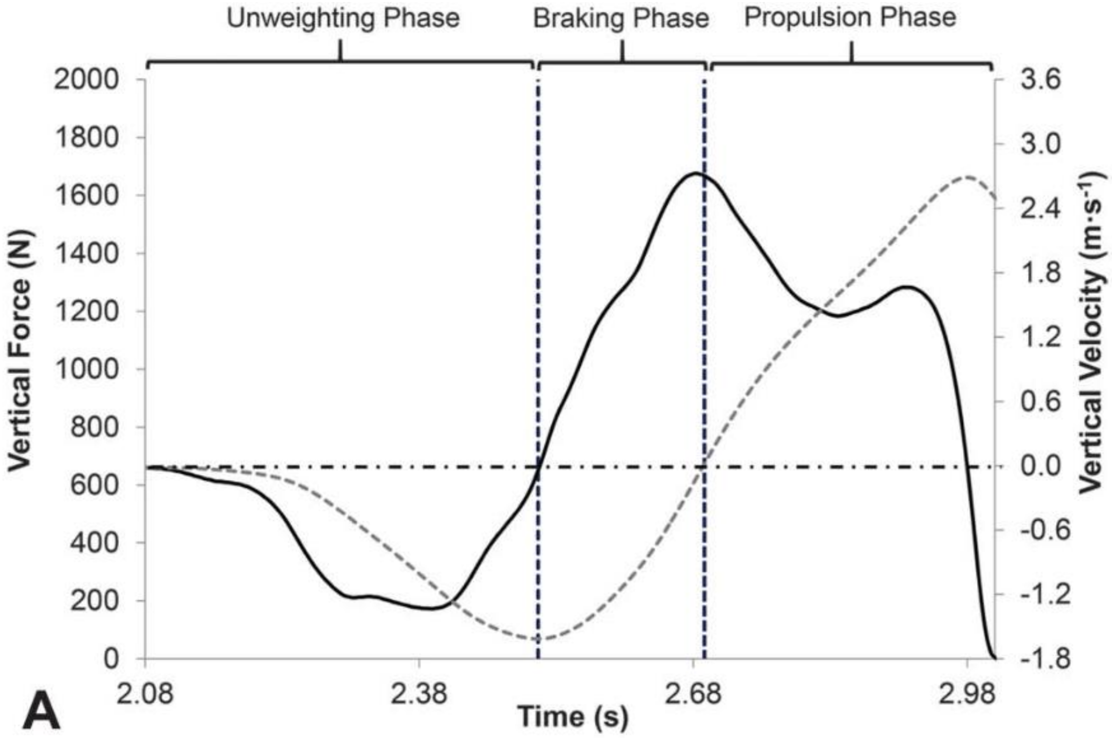

Figure 5.3A. Example force-time (solid black line) and associated velocity-time (dotted grey line) record for a CMJ between the onset of movement and take-off. The dash-dotted black line represents body weight (taken from McMahon et al. [25]).

The braking phase of the CMJ test is the period where the participant "actively" decelerates (i.e., "brakes") their COM [260]. The start of the braking phase is determined as (the frame after) the instant of peak negative COM velocity (Figure 5.3A) [25, 260]. This coincides with (the frame after) the instant that vertical GRF returns to body weight (Figure 5.3A). The end of the braking phase is determined as the instant the COM velocity returns to zero (Figure 5.3A) [25, 260]. This also coincides with the bottom of the countermovement (i.e., the peak negative COM displacement) (Figure 5.3B).

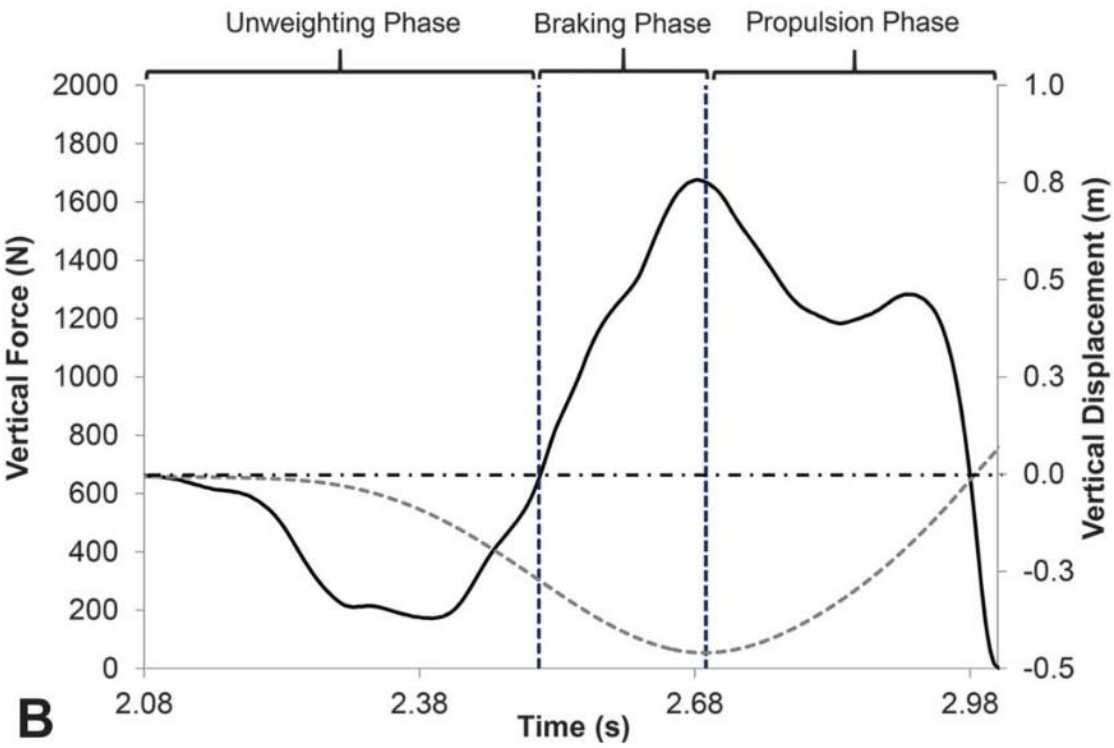

Figure 5.3B. Example force-time (solid black line) and associated displacement-time (dotted grey line) record for a CMJ between the onset of movement and take-off. The dash-dotted black line represents body weight (taken from McMahon et al. [25]).

The propulsion phase is the period where the participant "forcefully" extends their hips, knees, and ankles to vertically propel their COM [260]. The start of the propulsion phase is determined as the instant that COM velocity is positive (Figure 5.3A) [25, 260]. When conducting VJ jump assessments using force plates it is critical to be able to reliably identify when the end of the propulsion phase occurs, as an unsuitable determination would influence the calculation of several different kinetic and kinematic variables [263]. The end of the propulsion phase is also known as the "instant of take-off" [25, 264]. Various suitable force thresholds have been used to identify take-off and touchdown in literature [25]. Smith et al. [263] reported acceptable absolute (CV%) and relative (ICC) reliability across and trivial differences (based on Hedge's g) between methods such as when vertical GRF initially drops below 20 N, 10 N, 5 N, when the VGRF equals 0 N, when vertical GRF drops within five SDs of the first 300 ms of the flight phase, and when the VGRF drops below the peak residual force that occurs during the flight phase [263]. An issue with the "when vertical GRF drops within five SDs of the first 300 ms of the flight phase" method is that it requires a minimum of 300 ms of FT (~11 cm JH) to be achieved. Thus, integrating this method into a force plate system's proprietary software seems illogical as any test which did not meet this criterion would be deemed invalid. Taking the findings of Smith et al. [263] and the consideration for the issues with the 300 ms of FT method into account, the end of the propulsion phase is determined in the HD Inc. proprietary software utilising an arbitrary value as the instant that vertical GRF decreases below 25 N during positive COM velocity (i.e., the take-off threshold), which occurs due to the participant leaving the force plates (i.e., take-off) [260]. The flight phase starts at the instant of take-off (as described above) and consists of the participant leaving the force plate to attain positive vertical COM displacement [260]. This is reported in some studies as flight height (i.e., the flight height of the COM) [177] but reported via these methods as JH [260]. The apex of the jump (i.e., where peak positive COM displacement is achieved) (Figure 5.4A) coincides with a COM velocity of zero (Figure 5.4B). It is worth noting here that the estimation of JH was done utilising the TOV method (impulse-momentum theorem) throughout this thesis [230]. The estimation of JH utilising the FT method requires COM height to be the same at the instant of take-off and touchdown, as it assumes that the apex of the jump (peak positive COM displacement) occurs half-way through the flight phase [265]. Thus, differences in joint positioning between the instant of take-off and touchdown will affect JH calculated via FT. The landing threshold applied is the same arbitrary value as the take-off threshold in the HD Inc. proprietary software, where the flight phase ends at the instant that vertical GRF increases above 25 N for longer the 30 ms, which occurs due to the participant contacting (i.e., landing on) the force plates [260]. The end of the flight phase is therefore known as the “instant of touchdown” [25].

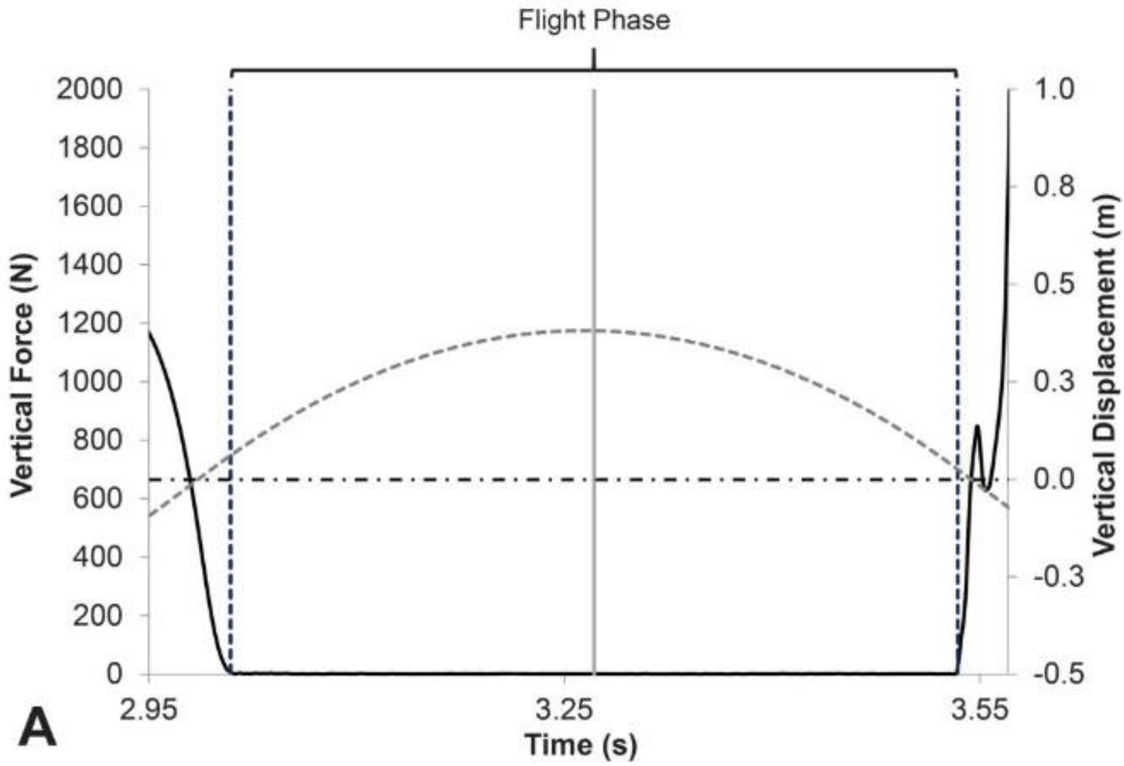

Figure 5.4A. Example force-time (solid black line) and associated displacement-time (dotted grey line) record for a CMJ between the instants of take-off and touchdown. The dash-dotted black line represents body weight. The vertical grey line represents the midpoint of the flight phase where peak COM displacement and zero COM velocity is achieved (taken from McMahon et al. [25]).

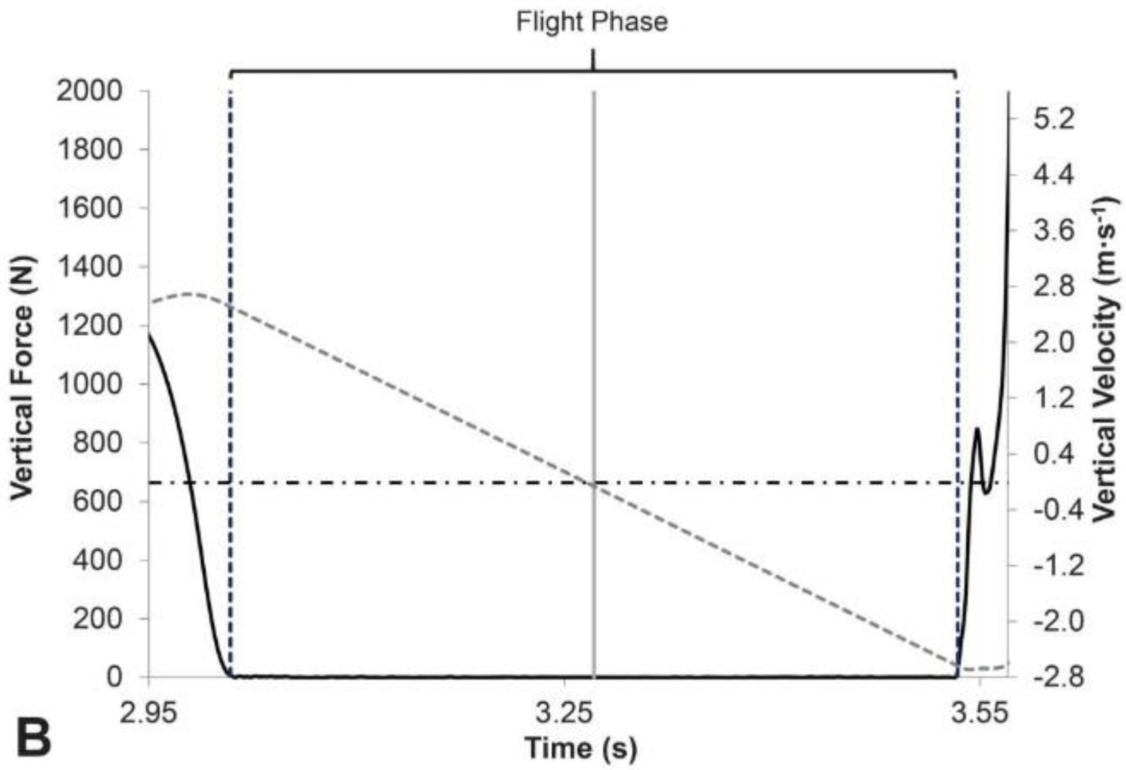

Figure 5.4B. Example force-time (solid black line) and associated velocity-time (dotted grey line) record for a CMJ between the instants of take-off and touchdown. The dash-dotted black line represents body weight. The vertical grey line represents the midpoint of the flight phase where peak COM displacement and zero COM velocity is achieved (taken from McMahon et al. [25]).

The landing phase consists of the participant landing on the force plates and decelerating (i.e., "braking") their COM, before standing upright in the same position adopted during the weighing phase [260]. This is typically characterised by the participant applying a net braking impulse which matches net propulsion impulse, as the participant decelerates their COM (i.e., their momentum) from a landing velocity (a.k.a., touch-down velocity) equivalent to their TOV [25, 171, 260]. The landing phase starts at the instant of touchdown (as described above) and ends at the instant that vertical GRF is within 5% of system weight for 200 ms (Figure 5.5) [260]. An examination of kinetic and kinematic metrics during the landing phase was not an area of interest throughout this thesis given the research produced has a physical "performance" focus. A limitation to focussing on the landing phase during testing is that propulsive phase kinetics and kinematics may be compromised. Thus, instructions were not provided during data collection relating to the strategy of landing, to ensure athletes focussed on achieving sufficient propulsive output.

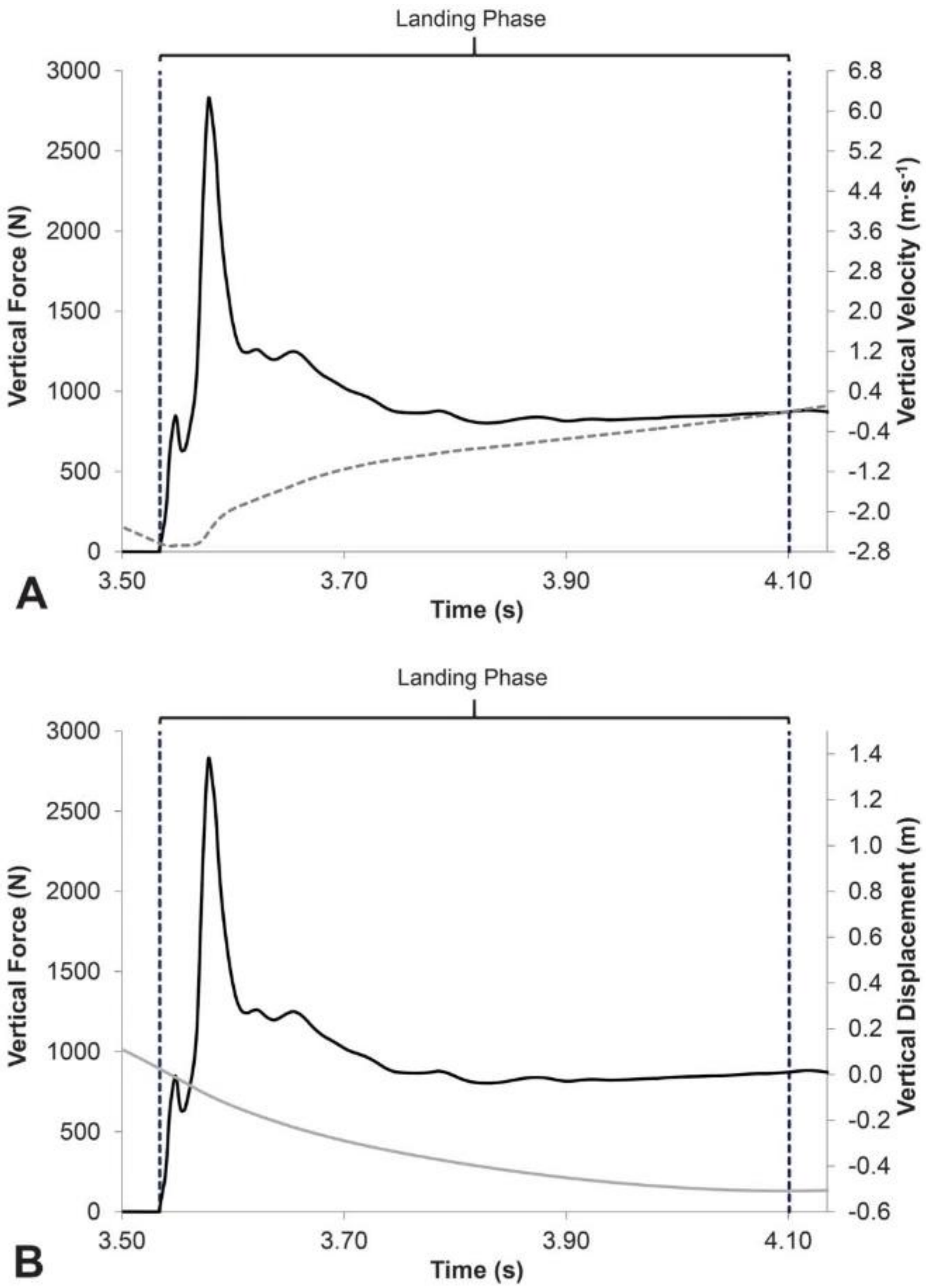

Figure 5.5. Example force-time (solid black line) and associated velocity-time (dotted grey line in Figure A) and associated displacement-time (solid grey line in Figure B) records for a CMJ after the instants of touchdown and end of the landing phase (taken from McMahon et al. [25]).

5.2.2.2 Variable Definitions

The variable definitions for the CMJ test, as reported in the HD Inc. metric database [260], are reported in Table 5.1.

Table 5.1. Variable Information for the Countermovement Jump Test.

Variables	**Unit of Measurement**	**Calculation**
mRSI	Arbitrary Unit (AU)	Jump Height divided by Time to Take-off.
FT:CT	Arbitrary Unit (AU)	Flight Time divided by Time to Take-off.
Jump Height	Metres (m)	The change in system COM position between the instant of take-off and peak positive vertical displacement of the system COM, calculated as take-off velocity squared divided by 19.62.
Flight Time	Seconds (s)	The time taken to complete the flight phase.
Jump Momentum	Kilogram-metre per second (kg·m/s)	The vertical velocity of the system COM at the instant of take-off multiplied by body mass.
Take-off Velocity	Metres per second (m/s)	The vertical velocity of the system COM at the instant of take-off.
Time to Take-off	Seconds (s)	The total time taken from the initiation of movement to the instant of take-off.
Stiffness	Newtons per metre (N/m)	Force at minimum displacement divided by countermovement depth.
Net Impulse Ratio	Arbitrary Unit (AU)	Net propulsive impulse divided by net braking impulse.
Relative Mean Propulsive Power	Watts per bodyweight (W/bw)	Mean propulsive power (mean propulsive force multiplied by mean propulsive velocity) divided by Body Weight.
Mean Propulsive Power	Watts (W)	The average mechanical power applied to the system COM during the propulsion phase (mean propulsive force multiplied by mean propulsive velocity).
Relative Peak Propulsive Power	Watts per bodyweight (W/bw)	Peak propulsive power (below) divided by Body Weight.
Peak Propulsive Power	Watts (W)	The peak instantaneous mechanical power applied to the system COM during the propulsion phase (propulsive force multiplied by propulsive velocity).
Peak Velocity	Metres per second (m/s)	The peak instantaneous vertical velocity of the system COM.

Mean Propulsive Velocity	Metres per second (m/s)	The average vertical velocity of the system COM during the propulsion phase.
Relative Mean Propulsive Force	Newtons per bodyweight (N/bw)	Mean propulsive force divided by Body Weight.
Mean Propulsive Force	Newtons (N)	The average vertical ground reaction force applied to the system COM during the propulsion phase.
Relative Peak Propulsive Force	Newtons per bodyweight (N/bw)	Peak propulsive force divided by Body Weight.
Peak Propulsive Force	Newtons (N)	The peak instantaneous vertical ground reaction force applied to the system COM during the propulsion phase.
Propulsive Phase Time	Seconds (s)	From when velocity exceeds 0.01 $m \cdot s^{-1}$ (which usually occurs one sample after the instant of zero velocity [i.e., end of the braking phase]), to the instant of take-off.
Force at Minimum Displacement	Newtons (N)	The vertical ground reaction force applied to the system COM at the point of the peak negative vertical displacement of the system COM.
Countermovement Depth	Metres (m)	The peak negative vertical displacement of the system COM.
Braking RFD	Newtons per second (N/s)	The average slope (from the start to the end of the braking phase) of the vertical ground reaction force applied to the system COM during the braking phase.
Relative Mean Braking Power	Watts per bodyweight (W/bw)	Mean braking power (mean braking force multiplied by mean braking velocity) divided by Body Weight.
Mean Braking Power	Watts (W)	The average mechanical power applied to the system COM during the braking phase (mean force multiplied by mean velocity).
Relative Peak Braking Power	Watts per bodyweight (W/bw)	Peak braking power (below) divided by Body Weight.
Peak Braking Power	Watts (W)	The peak negative instantaneous mechanical power applied to the system COM during the braking phase (force multiplied by velocity).
Net Braking Impulse	Newtons per second (N/s)	The net vertical impulse applied to the system COM during the braking phase.
Relative Mean Braking Force	Newtons per bodyweight (N/bw)	Mean braking force divided by Body Weight.

Mean Braking Force	Newtons (N)	The average vertical ground reaction force applied to the system COM during the braking phase.
Relative Peak Braking Force	Newtons per bodyweight (N/bw)	Peak braking force divided by Body Weight.
Peak Braking Force	Newtons (N)	The peak instantaneous vertical ground reaction force applied to the system COM during the braking phase.
Braking Phase Time	Seconds (s)	The period between the (sample after the) instant of peak negative velocity and the instant of zero velocity.
Unweighting Phase Time	Seconds (s)	The time taken to complete the unweighting phase.
Body Weight	Newtons (N)	The lowest 1 second average of the vertical ground reaction force applied to the system COM during the weighing phase, identified via an optimization loop.

5.3 DROP JUMP

5.3.1 Data Collection

Because participants performed all trials with arms akimbo and were instructed to jump "as fast and high as possible", the DJ test was not performed to solely minimise GCT, nor to solely maximise JH. However, a consistent GCT of <250 ms was required for the test to indicate fast SSC (i.e., plyometric) capacity [158, 229]. If a trial was not performed with this desired technique, participants were reminded of the verbal cues in the rest period before the commencement of the next trial.

An image of the starting position for the CMJ test is provided below (Figure 5.6). For the DJ trials, participants stepped onto a 30 cm box placed level with and 2 cm behind the force plate system on the force plates' foam surround, as seen in previous literature [171, 266]. Following a "flash and beep" command from the tablet's proprietary software, participants dropped (without stepping down or jumping upwards) from the box onto the force plates and performed a maximal effort DJ. This was standardised with the aim of preventing an addition or reduction in fall height from the standardised box height so that comparisons across athletes were fair. After landing, athletes stood completely upright (extended hips and knees) and motionless for at least one second [171]. This was done to enable the potential for the subsequent determination of body weight if the data was exported and analysed separately (e.g., in Microsoft excel) via the vertical GRF averaged over the final second of data collection method, as seen in previous research [171]. Vertical GRF data was collected over six seconds, at a sampling frequency of 1000 Hz.

Figure 5.6. Starting Position of the Drop Jump Test.

5.3.2 Data Analysis

5.3.2.1 Phase Descriptions

The proposed 5 "phases" identified in the HD Inc. calculations are termed the preparation, braking, propulsions, flight, and landing phases [260]. The tester inputs (records) the box height of the trial into the tablet prior to the commencement of a trial. The preparation phase involves the period where the force plates are unloaded, and the participant is stood on the box ready for the test to be initiated. An overview of the specific data collection procedures for the DJ are outlined above, however, this phase includes the tester initiating the test and, upon instruction, the participant will step out (not up or down) and drop from the box towards the force plates [260]. Unlike the CMJ test [25], system weight is not determined in the first phase of the DJ test using the HD Inc. system [260]. Instead, body weight is sourced from a CMJ, CMRJ, or Weighing Protocol trial (Table 5.2) [260].

The same as described for the CMJ test [25], the braking phase is the period where the participant "actively" decelerates (i.e., "brakes") their COM [260]. However, in the DJ this is preceded by a "free-fall" by the participant, as opposed to an unweighting phase described in the CMJ [25]. The start of the braking phase for the DJ test is determined as the instant that vertical GRF increases above 25 N for longer than 30 ms (i.e., the landing threshold), which occurs due to the participant contacting (i.e., landing on) the force plates [260]. This is the same threshold as the landing phase of the CMJ test [25]. Consequently, the start of the braking phase corresponds to the "instant of touchdown" [25]. The start of numerical integration of a DJ test trial using the HD Inc. system is determined via the first frame of the instant that vertical GRF increases above 25 N for longer the 30 ms, (i.e., the start of the braking phase) which corresponds to the "instant of touchdown" [25]. The method used for integration is the trapezoidal rule [260]. The end of the braking phase is determined as the instant the COM velocity equals zero, which is the same as described for the CMJ, and also coincides with the bottom of the descent (i.e., the peak negative COM displacement) [260]. Thus, the braking phase for the DJ test is defined as the period between the (sample after the) instant of touchdown and the instant of zero velocity [171, 260]. The start and end thresholds and actions of the propulsion, flight, and landing phases of the DJ test are the same as those described for the CMJ test [25, 260].

5.3.2.2 Variable Definitions

All variable definitions for the DJ test, as reported in the HD Inc. metric database [260], are the same as those of the CMJ test except the method of calculation of body weight, braking depth replacing the equivalent countermovement depth in the CMJ test, GCT replacing time to take-off, FT:CT subsequently being calculated using GCT and not time to take-off, and RSI replacing mRSI which is also calculated differently [260]. The definitions of these variables independent to the DJ test are reported in Table 5.2.

Table 5.2. Variable Information for the Drop Jump Test.

Variables	**Unit of Measurement**	**Calculation**
RSI	Arbitrary Unit (AU)	Jump Height divided by Ground Contact Time.
FT:CT	Arbitrary Unit (AU)	Flight Time divided by Ground Contact Time.
Ground Contact Time	Seconds (s)	The total time taken from initial contact (landing threshold set at arbitrary value of vertical GRF increasing above 25 N for longer than 30 ms) to the instant of take-off (take-off threshold set at arbitrary value of vertical GRF decreasing below 25 N during positive COM velocity).
Braking Depth	Metres (m)	The peak negative vertical displacement of the system COM.
Body Weight	Newtons (N)	Sourced from CMJ, SJ, CMRJ, or Weighing Protocol, but can be overridden with user input.

5.4 COUNTERMOVEMENT REBOUND JUMP

5.4.1 Data Collection

The CMRJ consists of two components, a preliminary maximal effort CMJ (i.e., the "CMJ portion"), followed immediately by a RJ. Participants performed all trials with arms akimbo and were instructed to jump "as fast and high as possible". For the CMRJ test, this applied to both the CMJ and RJ portions of the test. Thus, the RJ portion of the CMRJ was not performed to solely minimise GCT, nor to solely maximise JH, but a consistent GCT of <250 ms was required for the test to evaluate fast SSC capacity [158, 229]. If a trial was not performed with the desired criteria (e.g., if subjects' CMJ portion JH changed by ± 2 cm between trials, or RJ portion GCT exceeded 250 ms), participants were reminded of the verbal cues in the rest period before the commencement of the next trial.

The starting position of the CMRJ test is the same as the CMJ test (Figure 5.2). Participants stepped onto the force plates, stood completely upright (extended hips and knees) and motionless for at least one second before completing a maximal effort following a "flash and beep" command from the tablet's proprietary software. Participants stood completely upright (extended hips and knees) and motionless for the initial one second of data collection [59] to enable the subsequent determination of their body weight (vertical GRF averaged over the initial second of data collection). Vertical GRF data was collected over five seconds, at a sampling frequency of 1000 Hz.

5.4.2 Data Analysis

5.4.2.1 Phase Descriptions

The phase descriptions of the CMJ portion correspond to those of the CMJ test, including the weighing, unweighting, braking, propulsion, and flight phases [260]. The descriptions of these CMJ phases can be found in section 5.2.2.1. The CMJ portion does not include a landing phase (as is described for the CMJ test [25]) as the braking phase of the RJ portion is initiated upon landing, as is the case for the DJ test [260]. Accordingly, the phase descriptions of the RJ portion of the CMRJ test correspond to those of the DJ test, including the braking, propulsion, flight, and landing phases [260]. The descriptions of these RJ phases can be found above [260]. For the CMRJ test, body weight is calculated during the weighing phase of the CMJ portion [260]. The description for how body weight is calculated during the CMJ test can be found in Table 5.1. The start of numerical integration of a CMRJ test trial using the HD Inc. system is the same as described for the CMJ test, which is determined via a backwards search of 200 ms (using the previously mentioned optimization loop) from the initiation of movement threshold to the closest value of system weight, using the methods of the trapezoidal rule [25, 260].

5.4.2.2 Variable Definitions

All variable definitions for the CMJ portion of the CMRJ test are the same as those described for the CMJ test, including the description and method of calculation of body weight (Table 5.1). All variable definitions for the RJ portion of the CMRJ test are the same as the DJ test, except body weight, as explained (Table 5.2).

5.5 ISOMETRIC MID-THIGH PULL

5.5.1 Data Collection

An image of the starting position for the IMTP test is provided in figures 5.7A and 5.7B. For the IMTP test, testing was performed in line with established recommendations [187].

A portable isometric rig was used (Absolute Performance, Cardiff, Wales) [187, 188, 267], and participants were placed in a posture that represents the start of the second pull phase of the clean (i.e., mid-thigh clean-pull position) [187, 267].

The testers ensured the participants were in the correct posture, with the spine in a neutral upright position, and flexion at the knees (approx. 125 to 145 degrees) and hips (approx. 140 to 150 degrees relative to the thighs) [187]. Hands gripped the bar with a “clean grip”, feet were placed at a standardised shoulder width, with lifting straps applied by the tester to ensure that grip strength was not a limiting factor [193].

Participants were instructed to refrain from leaning on or applying “pre-tension” (>50 N) to the bar prior to each trial [24]. A visual inspection of the force-time trace allowed for the identification of pre-tension by ensuring there were <50 N differences in force during the initial phase of data collection [187, 268]. However, participants were asked to retract and depress their scapula in the starting position, which placed shoulder above or slightly ahead of the bar, to allow for all “slack” (i.e., caused by elbow flexion and shoulder girdle elevation/protraction) to be removed from the body, because this would result in an undesirable change in joint angles during maximal effort trials [269].

A minimum of 1s of quiet standing was applied immediately from the initiation of the test, which is a pre-set standardised protocol in the tablet’s proprietary software for the determination of body weight. Once this requirement is met, the tablet’s proprietary software provided a “flash and beep” command to commence the maximal effort IMTP trial, whilst the tester provided a repeated “PUSH!” command for 5s. Participants were instructed to push into the force plates “as fast and hard as possible”. The aim for the verbal cueing was to encourage a rapid and maximal application of vertical GRF [187]. The vertical component of the raw GRF data was collected over eight seconds, at a sampling frequency of 1000 Hz.

Figure 5.7A. Starting Position of the Isometric Mid-Thigh Pull Test (Frontal Plane).

Figure 5.7B. Starting Position of the Isometric Mid-Thigh Pull Test (Sagittal Plane).

5.5.2 Data Analysis

5.5.2.1 Phase Descriptions

The IMTP test has been prescribed 2 distinct phases in the HD Inc. metric database [260] consisting of the weighing and push phases [260]. The weighing phase consists of the participant standing on the force plates in a posture that represents the start of the second pull phase of the clean [260], as described above [267]. As is described for the CMJ test in page 118, and following the recommendation of Owen et al. [248], the weighing phase starts at the initiation of data collection on the tablet application by the tester and ends at the instant that the SD of vertical GRF is less than 25 N for 1 s [260]. Once this condition is met, the tablet's proprietary software provides a "flash and beep" command, to instruct the participant to initiate the push phase. A standardised threshold of 25 N (2.55 kg) ensures that the 1 s average of vGRF during the weighing period is not highly variable, providing further confidence in the accurate calculation of bodyweight. However, as described in page 118, the rationale for specifically utilising a 25 N threshold (e.g., as opposed to a 20 N threshold) is not provided in the HD Inc. metric database [260] or information packet [261] and it is not a changeable protocol given it is standardised in their proprietary software. The push phase consists of participants "pushing" into the force plates while simultaneously pulling on the bar "as fast and hard as possible", for 5 seconds [24, 192, 260, 270]. Researchers have recently favoured informing athletes prior to the initiation of the test to "push against the force plates whilst simultaneously pulling the bar as fast and hard as possible" [24, 192, 270], to avoid participants focussing on solely "pulling" on the bar with their upper-body during trials, in favour of attempting to "push" into the force plates with their lower-body to generate rapid and maximal vertical GRF.

Dos'Santos et al. [268] produced recommendations regarding identifying the onset of contraction for the IMTP test, suggesting it best practice to utilise a SD (i.e., 5 SD) of bodyweight method over relative (e.g., 2.5%, 5%, and 10%) bodyweight and arbitrary (e.g., 75 N) onset thresholds for accurately identifying IMTP force-time metrics such as peak force, time-specific force values (100, 150 and 200 ms), and RFD during 0-100 ms, 0-150 ms, 0-200 ms. Following these recommendations, the start of the push phase is determined in the HD Inc. proprietary software as the instant that vertical GRF exceeds more than 3 SDs of body weight calculated during the weighing phase for > 200 ms (i.e., the initiation of contraction threshold) [260]. The rationale for specifically utilising a 3 SD threshold (e.g., as opposed to a 5 SD threshold) is not provided in the HD Inc. metric database [260] or information packet [261] and it is not a changeable protocol given it is standardised in their proprietary software. The end of the push phase is determined by the tester instructing the participant to "relax" after the 5 second maximal effort, which allowed an additional < 3 seconds (8 seconds total test time) to compare the force-time trace to body weight to check if pre-tension occurred during the weighing period. The end of the test was determined by reaching the end of the arbitrary length of time entered by the tester onto the tablet prior to test commencement [260]. The start of numerical integration of an IMTP test trial using the HD Inc. system is determined from the first frame of the initiation of movement threshold, using the methods of the trapezoidal rule [260].

5.5.2.2 Variable Definitions

The variable definitions for the IMTP test, as reported in the HD Inc. metric database [260], are reported in Table 5.3.

Table 5.3. Variable Information for the Isometric Mid-Thigh Pull Test.

Variables	**Unit of Measurement**	**Calculation**
Time to Peak Force	Seconds (s)	The time taken from the initiation of the pull to the instant of absolute (gross) peak vertical ground reaction force during the isometric test.
Peak Force	Newtons (N)	The gross peak instantaneous vertical ground reaction force applied during the isometric test (bodyweight not subtracted).
RFD 0-250 ms	Newtons per second (N/s)	The average slope of the vertical ground reaction force applied during the isometric test between 0 and 250 ms (i.e., gross force value at 250 ms divided by 250 ms).
Force at 250 ms	Newtons (N)	The peak instantaneous gross vertical ground reaction force applied at 250 ms during the isometric test.
Force at 200 ms	Newtons (N)	The peak instantaneous gross vertical ground reaction force applied at 200 ms during the isometric test.
RFD 0-150 ms	Newtons per second (N/s)	The average slope of the vertical ground reaction force applied during the isometric test between 0 and 150 ms (i.e., gross force value at 150 ms divided by 150 ms).
Force at 150 ms	Newtons (N)	The peak instantaneous vertical ground reaction force applied at 150 ms during the isometric test.

RFD 0-100 ms	Newtons per second (N/s)	The average slope of the vertical ground reaction force applied during the isometric test between 0 and 100 ms (i.e., gross force value at 100 ms divided by 100 ms).
Force at 100 ms	Newtons (N)	The peak instantaneous gross vertical ground reaction force applied at 100 ms during the isometric test.
RFD 0-50 ms	Newtons per second (N/s)	The average slope of the vertical ground reaction force applied during the isometric test between 0 and 50 ms (i.e., gross force value at 50 ms divided by 50 ms).
Force at 50 ms	Newtons (N)	The peak instantaneous gross vertical ground reaction force applied at 50 ms during the isometric test.
Force at 0 ms	Newtons (N)	The peak instantaneous gross vertical ground reaction force applied at 0 ms during the isometric test.

<u>EXPERIMENTAL STUDY 1</u>

6 THE VALIDITY OF HAWKIN DYNAMICS WIRELESS DUAL FORCE PLATES FOR MEASURING COUNTERMOVEMENT JUMP AND DROP JUMP VARIABLES

6.1 INTRODUCTION

Lower body NMF is most commonly evaluated during the performance of the CMJ and DJ tests [23, 266], utilising force plates which enable the direct collection of force–time data [161, 222]. Forward dynamics procedures are then used to calculate a multitude of variables from the resultant force–time curve, such as phase-specific velocity and displacement of the system's COM (which is equivalent to the body's when no external load is being held) [25]. The introduction of commercially available, portable, and affordable wireless dual force plate systems (hardware and software) means there is a new opportunity for applied sport scientists, S&C coaches, and researchers to gain detailed information about their athletes' NMF. This is important for researchers and practitioners who can now answer more authentic questions using wireless dual force plate data collected in practical real-world environments.

If force–time data are analysed instantly using bespoke proprietary software (i.e., those integrated into some force plate companies' mobile applications), these data can be used immediately to inform athletes, coaches, and medical staff about individual preparedness and to recommended exercise prescriptions [20, 25]. Although force plate testing is becoming commonplace in sport, accuracy must be maintained, as this is the main factor in determining an appropriate evaluation device [271]. Test results are only useful if the collection instruments (hardware and software) measure what they are supposed to (validity) [36]. Thus, the validity of any new technology should be established by quantifying the agreement between it and another well-established test device that is valid (i.e., a criterion "gold standard" device or method) [215, 272-275], and appropriate statistics are required to facilitate this purpose [276].

The validity of a new technology established by quantifying its agreement with a "gold standard" device is considered a type of criterion-referenced validity, specifically concurrent validity [36, 205]. Mullineaux et al. [276] discussed in detail the benefits, limitations, and suitability of various assessments of bias for the purpose of determining concurrent validity when comparing a measurement to a "gold standard" technique. A primary limitation to many tests of concurrent validity is that they do not provide an assessment of both fixed and proportional bias [276]. For this purpose, a test of mean difference (e.g., a paired *t*-test) or a correlation test (e.g., Pearson's correlation coefficient) between two test devices is considered insufficient [277]. Appropriate examples of tests which assess these biases include limits of agreement (LOA), ordinary least-squares regression (OLSR), and ordinary least products regression (OLPR) analyses. A limit to OLSR analysis is that it only assumes error in a single measurement, where when determining the validity of biomechanical apparatus or techniques the criterion method would also demonstrate a level of measurement error (e.g., when comparing force plate technologies), making this method inappropriate for such a purpose [276]. The LOA analysis is comparatively simple to conduct and produces results which are easy to interpret given they are reported in units of measurement [272], but is limited in that it does not account for the effects of fixed and proportional bias independently, which is critical as fixed and proportional biases often interact [215, 273-276, 278, 279]. For example, an LOA analysis could present a zero mean difference as a result of a positive proportional bias and negative fixed bias [276].

The only "philosophically" correct statistical technique to assess concurrent validity is through OLPR analysis, which provides a separate assessment of fixed and proportional bias as well as a prediction equation [273, 276]. Authors of previous research centered on determining the concurrent validity of biomechanical devices such as force plates [57], bar-mounted velocity-based training devices [271], and force plate data collection procedures [171] have successfully utilised OLPR analyses for the benefits of providing an estimation of fixed and proportional bias in comparison to a "criterion" method. For interpreting results, fixed and proportional biases have been defined as referring to a "none zero intercept" and "a slope not equal to 1" in OLPR analyses, respectively [279]. Practically, it is a means to determine if the 95% confidence interval (CI) of the intercept and slope deviate from the ideal [279]. The validity of the HD Inc. and ForceDecks (v2.0.7782) proprietary software has been appropriately investigated in previous research via OLPR analyses, in comparison to a criterion MATLAB script [20]. The authors reported a small magnitude of error for force–time variables from the CMJ, DJ, SJ, and IMTP tests using the HD Inc. software compared to a criterion MATLAB script [20]. This was attributed to similarities in analysis procedures between HD Inc. and MATLAB, such as phase identifications along the force–time curve and the utilisation of appropriate metric definitions and calculations [20].

One study to date, presented as a conference poster, aimed to establish the concurrent validity of the HD Inc. force plate hardware, but with limited statistical analyses (i.e., Pearson's correlation coefficients and Bland–Altman plots, and not OLPR), and reporting of only CMJ outcome variables [280]. Similarly, researchers previously established the concurrent validity of portable 1-dimensional (i.e., collect vertical GRFs only) [57] and 2-dimensional (i.e., collect vertical and horizontal GRFs) [281] PASCO force plate options against a criterion device (i.e., a fixed in-ground Kistler force plate system), but did not include the assessment of bias using appropriate statistics (i.e., OLPR statistics) [57, 281]. To establish system accuracy, determining any systematic disagreement between said apparatus and a widely used and thoroughly investigated "gold standard" system using appropriate agreement statistics is critical [184, 273]. Due to the validity of the HD Inc. software having been established [20], an assessment of the validity of the HD Inc. force plate hardware using appropriate agreement statistics is required to provide confidence to users regarding the accuracy of the hardware.

Therefore, the purpose of this study was to determine the concurrent validity of the HD Inc. force plate hardware by assessing the agreement between selected outcome (e.g., JH, FT, etc.) and strategy (e.g., time to take-off, GCT, etc.) variables during the CMJ and DJ tasks, compared to those derived from a laboratory-grade, in-ground force plate system (i.e., a "gold standard"). It was hypothesised that agreement would be found between the force plate systems for all CMJ and DJ variables with no fixed or proportional bias present. The results of this study will inform the use of the HD Inc. force plate system in future research projects and in applied sports settings where system accuracy is paramount.

6.2 METHODS

6.2.1 Participants

Twenty recreationally active adults (age = 27 ± 6 years, body mass = 85 ± 14 kg, height 176.5 ± 9.23 cm) with varied sports backgrounds (e.g., amateur soccer, netball, weightlifting, etc.) and who were free from any injury that would prevent them performing maximum effort trials volunteered to participate in the study. Current training status and previous resistance and VJ training experience were not a limiting factor in this study, due to its focus on agreement between the two force plate systems alone. Informed consent was provided, and the study was pre-approved by the Institutional Ethics Committee (application ID 2768) before recruitment and testing commenced.

6.2.2 Design

A cross-sectional design was employed, whereby testing was conducted during a single session in the human performance laboratory at the University of Salford on 17th December 2021. A standardised warm-up (~10 min) consisting of dynamic stretching and submaximal CMJs and DJs was performed by each participant prior to testing to reduce the risk of injury.

6.2.3 Force Plate Setup

An HD Inc. force plate system (3rd Generation, model 0484; Westbrook, Maine, USA) consisting of two portable adjacent force plates was placed directly on top of and within the dimensions of two adjacent Advanced Mechanical Technology, Inc. (AMTI; Model Biomechanics Measurement Series 400600; Watertown, MA, USA) in-ground force plates to collect the GRF produced through each leg independently and simultaneously at 1000 Hz (Figures 1 and 2). The GRF data were sampled for five (CMJ) and six (DJ) seconds using HD Inc. proprietary software and Qualisys Track Manager software (Qualisys Ltd., Gothenburg, Sweden) for the HD Inc. and AMTI systems, respectively. Both systems were zeroed before each trial so that the weight of the HD Inc. system was removed from the AMTI system before data acquisition. The raw (i.e., unfiltered) vertical component of the GRF data series was exported from each force plate system's software to Microsoft Excel, which was used to analyse the bilateral forces (summed left and right leg forces) using a custom spreadsheet. The vertical GRF data exported from both force plate systems were analysed identically using the custom spreadsheet.

Figure 6.1. Example set-up for data collection (frontal plane).

Figure 6.2. Example set-up for data collection (sagittal plane).

6.2.4 Countermovement Jump

All CMJ trials were performed following the criteria described in section 5.2.1. Data Collection. Data analysis procedures including phase descriptions and metric calculations were the same as described in section 5.2.2. Data Analysis, except the power applied to the COM was determined by multiplying force by velocity on a sample-by-sample basis [249], and take-off and touchdown force thresholds for the CMJ were determined as equal to 5 SDs of the vertical GRF during the first 300 ms of flight [248]. Due to the AMTI system demonstrating greater flight-phase force (i.e., noise), the AMTI system's take-off and touchdown thresholds were used for both systems. For comparison, 5 SDs of the vertical GRF during the first 300 ms of the flight phase equalled ~16 N vs. ~8 N for the AMTI and HD Inc. systems, respectively; thus, 16 N was applied to both systems. The 16 N take-off threshold was used to time-align the CMJ data between the AMTI and HD Inc. systems. This was necessary as the AMTI data capture was triggered first, followed immediately by HD Inc. data capture. Thus, there were more AMTI data prior to take-off and so the difference in vertical GRF samples between systems from the start of capture to take-off was deducted from the AMTI data (Figure 6.3). The CMJ phases were identified using methods explained and used recently [25]. The braking phase was defined as the period between the instant of peak negative velocity and the instant of zero velocity [171]. The propulsive phase was defined as the period between the velocity exceeding 0.01 m/s and the instant of take-off [171]. The CMJ variables included in the analyses and a description of how they were calculated are shown in Table 6.1.

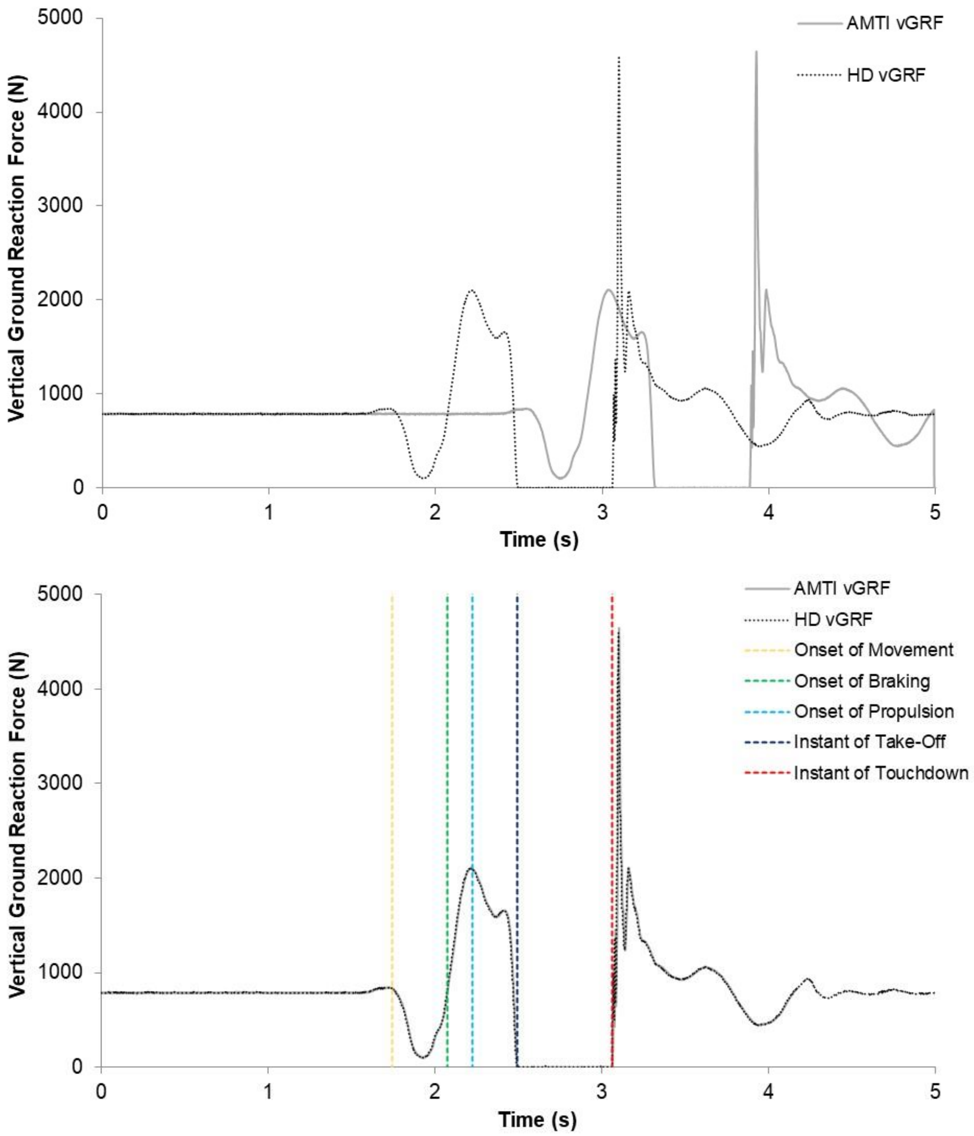

Figure 6.3. A representative example of an original (top) and time-aligned (bottom) CMJ trial recorded by the AMTI (solid grey line) and HD Inc. (dotted black line) force plate systems. The bottom graph also illustrates the occurrence of key events. vGRF = vertical ground reaction force.

Table 6.1. Selected force–time variable calculations.

Variables	Calculation	CMJ?	DJ?
RSI (AU)	Jump Height divided by Ground Contact Time.		X
mRSI (AU)	Jump Height divided by Time to Takeoff.	X	
Jump Height (m)	The change in centre of mass position between the instant of take-off and peak positive vertical displacement of the centre of mass during the flight phase, calculated as takeoff velocity squared divided by 19.62.	X	X
Flight Time (s)	The time taken to complete the flight phase.	X	X
Ground Contact Time (s)	The total time taken from instant of touchdown the instant of take-off.		X
Time to Takeoff (s)	The total time taken from the onset of movement to the instant of take-off.	X	
Mean Propulsive Power (W)	The mean mechanical power applied to the centre of mass during the propulsive phase.	X	X
Peak Propulsive Power (W)	The peak instantaneous mechanical power applied to the centre of mass during the propulsive phase.	X	X
Peak Propulsive Velocity (m/s)	The peak instantaneous vertical velocity of the centre of mass during the propulsive phase.	X	X
Net Propulsive Impulse (N.s)	The net vertical impulse applied to the centre of mass during the propulsive phase.	X	X
Mean Propulsive Force (N)	The mean vertical ground reaction force applied to the centre of mass during the propulsive phase.	X	X
Peak Propulsive Force (N)	The peak instantaneous vertical ground reaction force applied to the centre of mass during the propulsive phase.	X	X
Stiffness (N/m)	Peak braking force divided by braking depth.		X
Braking Depth (m)	The peak negative vertical displacement of the centre of mass during the braking phase.		X
Countermovement Depth (m)	The peak negative vertical displacement of the centre of mass during the braking phase.	X	
Mean Braking Power (W)	The mean mechanical power applied to the centre of mass during the braking phase.	X	X
Peak Braking Power (W)	The peak negative instantaneous mechanical power applied to the centre of mass during the braking phase.	X	X
Net Braking Impulse (N.s)	The net vertical impulse applied to the centre of mass during the braking phase.	X	X
Mean Braking Force (N)	The mean vertical ground reaction force applied to the centre of mass during the braking phase.	X	X
Peak Braking Force (N)	The peak instantaneous vertical ground reaction force applied to the centre of mass during the braking phase.	X	X

Key: RSI, reactive strength index; mRSI, modified reactive strength index; AU, arbitrary unit; m, metres; s, seconds; W, watts; N, Newtons; CMJ, countermovement jump; DJ, drop jump; X, included.

6.2.5 Drop Jump

For the DJ trials, participants stepped onto a 45 cm box placed 2 cm behind the force plate system (Figures 1 and 2). However, because the HD Inc. force plates had a height of 6.5 cm, but were positioned on top of the AMTI force plates 1.5 cm below the rubber surface the box was placed on, the distance from the box to the top surface of the force plates (i.e., effective box height) was 40 cm. This was arranged because 40 cm is a commonly used box height for DJ assessments, following proposed methods for evaluating DJ performance using only one on-ground force plate system [282]. Following a "3, 2, 1, drop" command, participants dropped (without consciously stepping down or jumping upwards) from the box onto the force plates and performed a maximal effort DJ with a focus on executing the jump with as short a contact time as possible whilst also aiming to maximise JH [230]. Following landing, participants stood completely upright (extended hips and knees) and motionless for at least one second [282]. Each participant's body weight was calculated by averaging the vertical force trace over the final one second of data collection when the subject was stationary on the force plates after landing [282].

The DJ vertical GRF data were time aligned between force plate systems by commencing data analysis (i.e., phase identification and numerical integration) from the first sample vertical GRF that surpassed a touchdown threshold of 25 N (Figure 6.4). Thus, no vertical GRF data from the AMTI system (which began data capture immediately before the HD Inc. system) that were recorded before touchdown were included in the analyses. A 25 N threshold was also used to identify take-off and the second touchdown (post DJ). The numerical integration of the vertical GRF–time record and identification of the braking and propulsive phases were conducted as per the CMJ data except that they began at the instant of touchdown.

The velocity with which one contacts the ground (i.e., the touchdown velocity) during DJ trials is determined by fall height [171], where it has been assumed that fall height would be equal to the prescribed box height in the DJ test [171]. However, McMahon et al. [171] reported average fall heights that were 10% and 14% less than prescribed 30 cm and 40 cm box heights, respectively, in DJ trials performed by 26 male sports science students (age = 23.8 ± 5.1 years, height = 1.80 ± 0.07 m, body mass = 81.2 ± 11.6 kg) with mixed sports backgrounds. Thus, touchdown velocity was calculated in this study using a one force plate method proposed by Baca et al. [282], and recently validated in the research of McMahon et al. [171], which involved correcting touchdown velocity by inspecting the velocity–time record during the final one second of data collection when subjects were stationary on the force plates after landing, where necessary. Specifically, touchdown velocity was first estimated from box height utilising the conservation of mechanical energy principle (square root of 2 × 9.81 × box height [0.40 metres]) [171, 282]. Numerical integration of the force–time record was performed by utilising this touchdown velocity initially and the body weight calculated during the final one second of data collection when the subject was stationary on the force plates after landing to yield COM velocity and displacement [171, 282]. Then, during the final one second of data recording where participants stood still for weighing, the mean velocity would have equalled 0 $m \cdot s^{-1}$ if fall height was equal to the prescribed box height [171, 282]. Any discrepancy between the mean velocity and 0 $m \cdot s^{-1}$ was then used to correct touchdown velocity [171, 282]. Then, the corrected touchdown velocity was used for numerical integration, and fall height was estimated as the corrected touchdown velocity squared divided by 2 × 9.81 [171, 282]. The DJ variables included in the analyses and a description of how they were calculated are shown in Table 6.1.

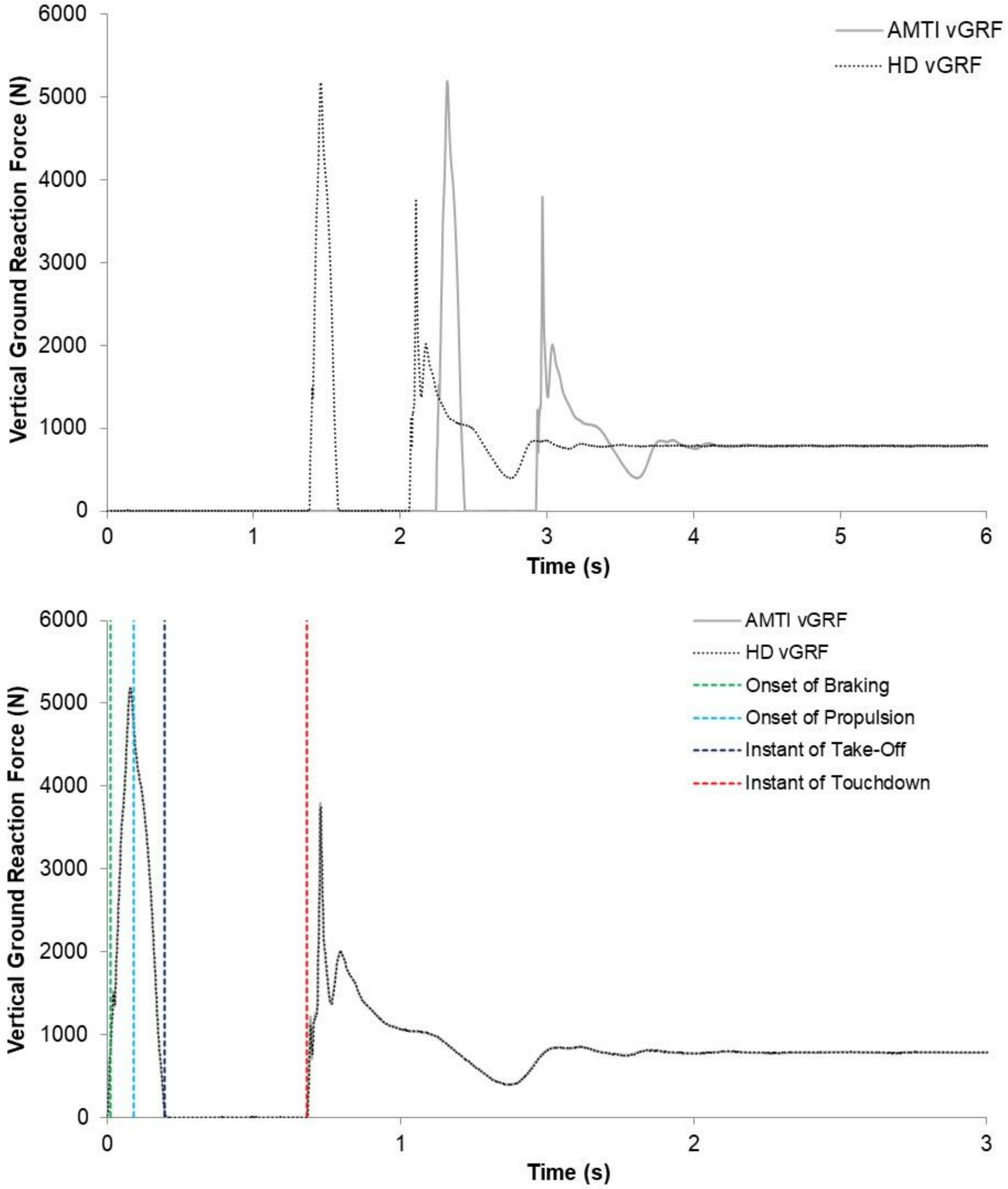

Figure 6.4. A representative example of an original (top) and time-aligned (bottom) drop jump trial recorded by the AMTI (solid grey line) and HD Inc. (dotted black line) force plate systems. The bottom graph also illustrates the occurrence of key events. vGRF = vertical ground reaction force.

6.2.6 Statistical Analyses

The average across three CMJ and DJ trials (for each variable) was taken forward for statistical analysis. Statistical analyses were performed using SPSS software (version 25; SPSS Inc., Chicago, IL, USA) using nonlinear regression and the user-defined loss function [273].

The agreement between force plate systems was determined via OLPR, which was conducted following recommendations in literature [184, 273, 276]. As per methods described by Mullineaux et al. [276], if the bootstrapped 95% CI for the intercept did not include 0, fixed bias was inferred to be present. If the bootstrapped 95% CI for the slope did not include 1, proportional bias was inferred to be present [276].

6.3 RESULTS

Descriptive statistics, OLPR coefficients, and corresponding bootstrapped 95% CIs are reported in Table 6.2 (CMJ) and Table 6.3 (DJ). For all CMJ variables investigated, there was no fixed or proportional bias between the two force plate systems. The same was seen for DJ variables except that both fixed and proportional bias were identified for peak braking power and proportional bias was identified for peak braking force.

Descriptive statistics (mean ± SD) for fall height and touchdown velocity for the AMTI and HD Inc. force plate systems are reported in Table 6.4. The mean fall height recorded on the AMTI and HD Inc. systems was approximately 5 cm less than the prescribed 40 cm effective box height (Table 6.4).

Table 6.2. Descriptive and agreement statistics for the selected CMJ variables.

Variables	AMTI (Mean ± SD)	HD (Mean ± SD)	Intercept *95% CI*	Slope *95% CI*
mRSI (AU)	0.43 ± 0.10	0.43 ± 0.10	0.00 *-0.01 to 0.00*	1.01 *0.99 to 1.04*
Jump Height (m)	0.31 ± 0.07	0.31 ± 0.06	-0.01 *-0.02 to 0.01*	1.03 *0.98 to 1.08*
Flight Time (s)	0.51 ± 0.05	0.51 ± 0.05	0.00 *-0.01 to 0.01*	1.00 *0.99 to 1.01*
Time to Takeoff (s)	0.76 ± 0.09	0.77 ± 0.09	-0.01 *-0.06 to 0.00*	1.01 *0.96 to 1.04*
Mean Propulsive Power (W)	2316.23 ± 481.89	2302.91 ± 480.00	4.24 *-33.80 to 42.29*	1.00 *0.99 to 1.02*
Peak Propulsive Power (W)	4124.56 ± 907.17	4107.07 ± 913.99	48.12 *-17.08 to 113.32*	0.99 *0.98 to 1.01*
Peak Propulsive Velocity (m/s)	2.59 ± 0.25	2.58 ± 0.24	-0.07 *-0.19 to 0.04*	1.03 *0.99 to 1.08*
Net Propulsive Impulse (N.s)	210.34 ± 41.74	209.25 ± 42.08	2.79 *-1.04 to 6.62*	0.99 *0.97 to 1.01*
Mean Propulsive Force (N)	1667.56 ± 291.81	1664.07 ± 290.81	-2.26 *-12.43 to 7.91*	1.00 *1.00 to 1.01*
Peak Propulsive Force (N)	2042.72 ± 343.63	2040.87 ± 343.97	3.92 *-5.25 to 13.09*	1.00 *1.00 to 1.00*
Countermovement Depth (m)	-0.30 ± 0.06	-0.30 ± 0.06	0.01 *-0.01 to 0.02*	1.01 *0.97 to 1.06*
Mean Braking Power (W)	-1092.83 ± 274.27	-1097.65 ± 273.88	6.37 *-2.11 to 14.85*	1.00 *0.99 to 1.01*
Peak Braking Power (W)	-1518.54 ± 426.54	-1524.72 ± 426.16	7.53 *-0.77 to 15.83*	1.00 *1.00 to 1.01*
Net Braking Impulse (N.s)	106.79 ± 25.06	107.32 ± 24.97	-0.91 *-2.07 to 0.26*	1.00 *0.99 to 1.02*
Mean Braking Force (N)	1495.80 ± 250.73	1498.44 ± 250.90	-1.58 *-10.66 to 7.49*	1.00 *0.99 to 1.01*
Peak Braking Force (N)	1951.83 ± 319.75	1952.70 ± 320.31	2.53 *-11.80 to 16.86*	1.00 *0.99 to 1.01*
Body Weight (N)	833.21 ± 141.92	833.69 ± 141.68	-1.88 *-7.80 to 4.03*	1.00 *1.00 to 1.01*

Key: AMTI, advanced mechanical technology, inc.; HD, Hawkin Dynamics; SD, standard deviation; CI, confidence interval; AU, arbitrary unit; m, metres; s, seconds; N, Newtons.

Table 6.3. Descriptive and agreement statistics for the selected DJ variables.

Variables	AMTI (Mean ± SD)	HD (Mean ± SD)	Intercept	Intercept 95% CI	Slope	Slope 95% CI
RSI (AU)	0.91 ± 0.30	0.89 ± 0.30	0.01	*-0.03 to 0.05*	1.01	*0.96 to 1.06*
Jump Height (m)	0.27 ± 0.05	0.26 ± 0.05	0.01	*-0.01 to 0.03*	0.98	*0.93 to 1.04*
Flight Time (s)	0.47 ± 0.05	0.47 ± 0.05	-0.01	*-0.02 to 0.00*	1.03	*1.00 to 1.05*
Ground Contact Time (s)	0.32 ± 0.11	0.32 ± 0.11	0.00	*0.00 to 0.00*	1.00	*1.00 to 1.01*
Mean Propulsive Power (W)	2726.90 ± 585.09	2678.15 ± 575.27	3.03	*-91.00 to 97.06*	1.02	*0.98 to 1.05*
Peak Propulsive Power (W)	4525.16 ± 984.45	4448.20 ± 961.74	-28.08	*-315.54 to 259.37*	1.02	*0.95 to 1.10*
Peak Propulsive Velocity (m/s)	2.42 ± 0.21	2.39 ± 0.22	0.12	*-0.17 to 0.42*	0.96	*0.85 to 1.07*
Net Propulsive Impulse (N.s)	195.39 ± 32.36	192.60 ± 31.68	-1.38	*-10.31 to 7.55*	1.02	*0.98 to 1.06*
Mean Propulsive Force (N)	2042.37 ± 425.30	2030.98 ± 422.18	-3.61	*-22.47 to 15.25*	1.01	*1.00 to 1.02*
Peak Propulsive Force (N)	3056.82 ± 839.12	3047.28 ± 837.84	4.92	*-5.46 to 15.29*	1.00	*1.00 to 1.01*
Stiffness (N/m)	19.46 ± 10.54	19.00 ± 10.30	0.02	*-0.48 to 0.51*	1.02	*0.99 to 1.06*
Braking Depth (m)	-0.23 ± 0.07	-0.23 ± 0.07	0.00	*-0.01 to 0.01*	1.00	*0.96 to 1.04*
Mean Braking Power (W)	3550.86 ± 925.72	3555.47 ± 890.29	-146.10	*-304.22 to 12.02*	1.04	*0.99 to 1.09*
Peak Braking Power (W)	8258.04 ± 2570.69	8119.93 ± 2228.50	**-1108.73**	***-1853.27*** *to* ***-364.18***	**1.15**	***1.06*** *to* ***1.25***
Net Braking Impulse (N.s)	224.53 ± 39.35	225.68 ± 38.33	-7.13	*-19.17 to 4.90*	1.03	*0.98 to 1.07*
Mean Braking Force (N)	2611.15 ± 647.27	2602.91 ± 638.87	-25.97	*-54.40 to 2.46*	1.01	*1.00 to 1.03*
Peak Braking Force (N)	4134.00 ± 1163.00	4076.00 ± 1106.00	-151.43	*-319.35 to 16.50*	**1.05**	***1.00*** *to* ***1.10***
Body Weight (N)	833.00 ± 142.00	833.00 ± 141.00	-2.78	*-9.60 to 4.03*	1.00	*1.00 to 1.01*

Key: AMTI, advanced mechanical technology, inc.; HD, Hawkin Dynamics; SD, standard deviation; CI, confidence interval; AU, arbitrary unit; m, metres; s, seconds; N, Newtons; **Red Text**, indicates identified bias.

Table 6.4. Descriptive statistics for selected DJ variables.

Variables	AMTI (Mean ± SD)			HD (Mean ± SD)		
Touch-down Velocity (m/s)	-2.36	±	0.26	-2.35	±	0.25
Fall Height (m)	0.35	±	0.04	0.35	±	0.04

Key: AMTI, advanced mechanical technology, inc.; HD, Hawkin Dynamics; SD, standard deviation; m, metres; s, seconds.

6.4 DISCUSSION

The purpose of this study was to determine the concurrent validity of a wireless portable dual force plate system by assessing the agreement between selected force–time variables collected during the CMJ and DJ tests using the test system and those collected using an in-ground AMTI system, considered a "gold standard". This was carried out because the validity of the HD Inc. proprietary software was established using the CMJ and DJ tests in previous research [20], and previous attempts to validate the HD Inc. hardware using only the CMJ test were performed with a lack of methodological and statistical distinction [280]. Based on the results of this study, the wireless dual force plate system can be considered a valid alternative to the criterion industry gold standard with respect to collecting CMJ and DJ force–time data, because the OLPR analysis showed no fixed or proportional bias between the two force plate systems for any of the CMJ variables (N = 17; Table 6.2), and bias was shown for only 2 out of the 18 DJ variables (Table 6.3).

6.4.1 Agreement Considerations

These findings support the conclusions of the sole previous study conducted with a similar approach [280]; however, the results here indicate a better agreement between the two force plate systems. This is likely due to this study having applied what may be considered a philosophically more robust methodological and statistical design approach. For example, in the study by Crowder et al. [280], it is unclear whether their participants performed three maximal effort CMJs separately on the HD Inc. and AMTI systems. This is an initial concern, as it is rare that participants will perform separate CMJ trials with identical force–time characteristics [283]. This introduces random error due to inherent biological variation, which confounds the mechanical variation under investigation. Additionally, the study by Crowder et al. [280] assessed the mean bias between systems for the CMJ outcome measure JH alone, without assessing agreement between the strategy metrics underpinning JH. In contrast, the present study performed a more thorough analysis by including both outcome and strategy variables in the CMJ test.

From a statistical perspective, the more robust OLPR analysis was chosen in this study, according to recommendations in previous literature [184, 273], as opposed to the Pearson's correlation coefficients and Bland–Altman plots with 95% LOA used by Crowder et al. [280]. Differences in data collection frequencies were also evident, with the AMTI system collecting at 1200 Hz, whereas the HD Inc. system collected at 1000 Hz [280] . This discrepancy can affect key events of the CMJ, such as onset of movement and take-off thresholds, although it is unknown by how much.

Additionally, Crowder et al. [280] allowed participants to use AS during trials, which adds another factor which could have affected the variability of trials if data were not collected simultaneously on both force plates. The authors highlighted that the inclusion of AS could have increased the variability of the trials, as has been seen in previous research [280]. Taken together, the methodological shortcomings of the Crowder et al. [280] study may explain why their LOA analysis showed that the average JH collected across three trials with the HD Inc. system could be expected to range from 7.10 cm lower to 7.63 cm higher than that measured by the AMTI system, which the authors of this study deem unacceptable.

Furthermore, the CMJ is used within a testing battery specifically as a measure of slow SSC capacity, and generally demonstrates lower rates (i.e., increased movement time) and magnitudes (i.e., lower peak braking and propulsive force) for specific force–time measures in comparison to tests of fast SSC capacity (i.e., the DJ test), when performed with the correct technique (i.e., cued to jump "as fast and high as possible", with a DJ GCT of <250 ms) (Tables 6.1 and 6.2). In the present study, we performed a more thorough analysis by also including outcome and strategy variables for the DJ test. These analyses may have been justified by the results of this study, which identified fixed and proportional bias in peak braking power and proportional bias in peak braking force for the DJ (Table 6.2), but not the CMJ (Table 6.1).

Peak braking force is a measure that has been of interest to research related to identifying injury risk mechanisms of the lower extremities (e.g., anterior cruciate ligament injuries) during drop landing and DJ tasks [261], and can be influenced by the strategy applied (i.e., a "stiffer" strategy with less ROM through braking would increase peak braking force) [230, 283].

A potential reasoning for the proportional bias in peak braking force in DJs is a difference in the resolution and accuracy (i.e., the precision) of the load cells used in the hardware. The HD Inc. hardware utilises four strain-gauge-based "beam" load cells per plate (one at each corner of the force plate) with a reported rounding resolution and accuracy of ±0.25 N and 0.1 N, respectively [170].

In contrast, laboratory-grade, in-ground force plate systems (i.e., the "gold standard") might use more expensive sensors with better resolution and accuracy (e.g., to ± 0.1 N per sample), but these usually come at a greater cost to the consumer. In this example, a sample of force–time data representing 0.8 N of vertical GRF would round lower to 0.75 N if using the HD Inc. hardware but would remain as 0.8 N if using the "gold standard" (e.g., the AMTI) hardware. Thus, as peak braking force increases, there is the potential for a greater accumulated difference in rounding per sample in the HD Inc. system which may have caused this discrepancy. Additionally, the raw vertical GRF was analysed in this study but filtering the force–time record may have improved the agreement in peak braking force. The proposed rounding errors which caused bias to be present in the peak braking force also extended to the peak braking power, because power was determined by multiplying force by velocity on a sample-by-sample basis.

Despite these findings, peak braking force and power only represent a single instant in time and may not contribute significantly to the outcome (i.e., they do not significantly affect the net propulsive impulse production or TOV) of VJ tasks. Moreover, based on additional calculations using linear regression (i.e., $y = mx - c$, as produced by plotting the grand mean of the two force plate systems against the percentage difference between the two force plate systems), the predicted percentage difference between force plate systems at 8000 N of DJ peak braking force (~40% larger than the mean grand mean reported in this study) is only 3.6%. Similarly, the predicted percentage difference between force plate systems for 12000 W of DJ peak braking power (~40% larger than the grand mean for this study) is only 5.7%. As such, the proportional bias demonstrated in peak braking force and peak braking power in the DJ test is relatively small, even at extreme predicted values for each metric, and likely falls within the expected SEM.

These findings are reasonable considering that the force plate systems produced by AMTI are more expensive stationary systems manufactured towards a clinical, laboratory-style market, but, in contrast, the HD Inc. system provides greater practicality at a lower price point, with its target consumers being practitioners working in the field. A change to more resolute and accurate sensors like those used in the AMTI system would result in large increases in the cost of production which would reduce the HD Inc. system's affordability for practitioners. However, despite the target consumers of the HD Inc. product being practitioners working in the field, the agreement demonstrated in this study illustrates an ability for the HD Inc. force plate system to also be a cheaper, more practical, and valid alternative in the clinical, laboratory-style force plate market.

6.4.2 Drop Jump Considerations

A proposed limitation to the DJ assessment is that previous research has reported differences between effective box height and actual fall height [169]. A difference in fall height would change the touchdown velocity and thus the force–time characteristics of the braking phase (e.g., a change in net braking impulse), and, if using the DJ as a task during training, it may affect the accuracy of the prescription of DJ TL. Using a sample of twenty-two physical education students, Geraldo et al. [170] observed a progressively increasing difference (an average of 2 cm increase in difference per 10 cm increment in effective box height) between effective box height and fall height at effective box heights of 20, 30, 40, and 50 cm using an AMTI force plate sampling at 1000 Hz, similar to the methods used in this study.

From as low as a 20 cm effective box height, Geraldo et al. [170] reported a fall height of 13.7 ± 1.6 cm which equated to an average difference of 6.3 cm. Discrepancies of this amount have also been reported in research with senior, elite, male rugby players, in which poor relative reliability was observed for average fall height which ranged from 14.87 to 29.85 cm [35]. Geraldo et al. [170] also reported a fall height of 29.4 ± 2.6 cm from an effective box height of 40 cm, which demonstrated an average difference of 10.6 cm. The results of the present study corroborate these findings, reporting a fall height of 0.35 ± 0.04 m from the same effective box height, equating to a lower average difference of 5 cm, which was the same for both the AMTI and HD Inc. systems (Table 6.2).

These results indicate that participants stepped down from the box by an average of 5 cm from the effective box height during each DJ trial. Therefore, caution is advised when comparing DJ performance between individuals or results from separate studies due to potential discrepancies between fall height and effective box height, as identified in this study (Table 6.2), and the variation in the amount of difference reported in previous research [169, 170] [34,35]. Inaccuracies in the calculated TDV will result in an incorrect calculation of force–time variables throughout the remainder of the task, such as net braking impulse. The study by Merrigan et al. [20] compared DJ data collected on a single portable Bertec Corp. force platform when analysed in MATLAB vs. HD Inc. proprietary software; however, the TDV was predicted based on box height (based on the work–energy theorem), which was assumed to be the same for every participant tested. Consequently, it can be suggested that the validation of some DJ force–time variables between software tools performed in this study is inaccurate due to inaccuracies in fall height and TDV [20]. Future research should continue to establish fall height if using the DJ test as an assessment tool due to the differences reported in this study between effective box height and fall height.

The results of this study confirm agreement of the HD Inc. force plate hardware with the gold standard for common CMJ and (most) DJ force–time measures. Additionally, previous research validated the HD Inc. proprietary software using the same assessments [20]. The bias in specific DJ variables identified in this study was attributed to load cell resolution and rounding, but the mean differences were not deemed to be meaningful. Taken together, in addition to the discrepancies between DJ effective box height and fall height identified in this study, future research should consider establishing the concurrent validity of both the hardware and software combined against a criterion hardware and software system whilst using tests (e.g., the 10/5 and CMRJ tests) which produce different magnitudes, rates, and frequencies of loading (i.e., vGRF production) and eradicate the issues of fall height discrepancies. Additionally, the strain-gauge "beam" load cell sensors of the HD Inc. force plates should be compared to other portable force plate systems including those that use piezoelectric sensors, as was performed in the previous research examining the concurrent validity of portable PASCO force plates (strain-gauge sensors) against criterion in-ground Kistler force plates (piezoelectric sensors) [57, 281].

6.4.3 Practical Considerations

Based on the present study's results, the HD Inc. system can be considered an accurate system to use in any setting, and as an alternative to traditional, nonportable, and more expensive in-ground force plate systems for the CMJ test. This consideration also extends to the DJ test except for peak braking force and peak braking power. Although these measures may be of interest in specific settings (e.g., for monitoring DJ peak braking force during injury rehabilitation), these measures represent only an instant in time and had no effect on the agreement of any of the other outcome or strategy variables assessed. Additionally, the predicted percentage differences for these metrics between systems at 40% above the presented grand mean were considered small and within the expected measurement error. These results are useful for practitioners who are seeking a force plate system to evaluate NMF using CMJs and DJs in sports, but are restricted by system complexity, location, and price.

Researchers and practitioners should be mindful that the data presented here are related to comparisons between two specific force plate systems (i.e., HD Inc. and AMTI) which both utilise strain-gauge-based beam load cells. The findings here cannot be extrapolated to provide a rationale to use the HD Inc. system over other force plate systems such as those which use piezoelectric load cells, for which agreement is yet to be determined. Additionally, the sample size is acknowledged as a limitation of the study. Whilst we acknowledge this, other studies that have assessed the concurrent validity of PASCO portable force plates for measuring CMJ variables used only 2 participants [281], albeit with several repetitions performed per participant, and a similar study by Lake et al. [57] utilised 28 participants.

6.5 CONCLUSIONS

The results of this study demonstrate that there is no fixed or proportional bias between the HD Inc. and AMTI (gold standard) force plate systems for measuring common CMJ strategy and outcome variables. Therefore, the HD Inc. force plate system may be considered a valid alternative to the industry gold standard for the assessment of CMJ force–time characteristics and thus may be confidently used for this purpose by researchers and practitioners alike.

The HD Inc. system is also a valid alternative to an industry gold standard force plate system for measuring common DJ force–time characteristics, because although bias was present for peak braking force and peak braking power, the predicted percentage differences at high metric values (8000 N and 12,000 W, respectively) were small and had no impact on any other outcome or strategy variables that are likely to be of interest to researchers and practitioners conducting DJ testing. Although accuracy has been established for the HD Inc. force plate system, it is still advised to utilise the same force plate system for each testing occasion (i.e., do not use the HD Inc. and AMTI systems interchangeably when testing athletes at different time points).

EXPERIMENTAL STUDY 2

7 TEST-RETEST RELIABILITY OF COUNTERMOVEMENT JUMP, DROP JUMP, COUNTERMOVEMENT REBOUND JUMP, AND ISOMETRIC MID-THIGH PULL FORCE-TIME VARIABLES IN SOCCER ATHLETES

7.1 INTRODUCTION

In team sports, player availability is directly associated with team success [284], where the teams experiencing less injuries typically outperform those who experience more injuries throughout the course of a competitive season [285]. Subsequently, maintaining high player availability through fatigue mitigation and injury prevention strategies is desirable [72, 74]. The "minimum effective dose" of training is often prescribed in sports with congested fixture schedules (e.g., professional soccer), where the aim is to *maintain* physical preparedness throughout specific periods of a season. This approach is prescribed to minimise fatigue in the acute term and thus reduce the amount of neuromuscular recovery required [73, 74], because acute negative alterations in physical preparedness can immediately effect on-field physical performance and increase the potential for non-contact injuries [72, 74]. However, adopting this approach usually comes at the sacrifice of optimal longitudinal developments of physical characteristics, which is concerning given it is known that low levels of muscular strength and pre-dispose athletes to injury [217], and negatively affect performance in field-based actions [286] such as linear sprint speed [199, 287] and COD speed [199, 200, 287].

Objective measures of physical capacity provide the most effective means of monitoring the magnitude and time course of changes in NMF resulting from physical activity [129]. Due to the advent of more commercially available, portable, and affordable hardware and software, with accuracy that has been validated against industry "gold standard" systems [20, 57, 163], a variety of force plate options are now widely accessible to practitioners looking to evaluate changes in athletes' NMF. Force-time data obtained during force plate testing is only beneficial if a test measures what it is supposed to (validity) and if the measurement is repeatable (reliability) [36]. Thus, reliability analyses must be performed to quantify measurement error to allow for the proper interpretation of test data [202], and the most common way to establish measurement error is to administer the same testing protocol on two separate occasions to the same group of athletes, known as a test-retest repeated-measures design [36, 205].

The CMJ and variations of RJ tests provide measures of "slow" and "fast" SSC capacity, respectively [23, 25, 26, 59, 67, 118, 160, 161, 165, 171, 172, 264, 288, 289]. The CMJ is the most commonly utilised test for evaluating NMF in the football codes [23]. At least six key phases (i.e., weighing, unweighting, braking, propulsion, flight, and landing) of the CMJ test can be identified from each CMJ force-time record when the data has been collected appropriately [290]. The test-retest reliability of a variety of force-time metrics obtained during different phases of the CMJ has been reported in recent studies involving team-sport athletes [65, 68-70, 291, 292], where better reliability for metrics that were calculated during the propulsive rather than the countermovement (i.e., the unweighting and braking phases) phase of the CMJ test have been reported [65, 68-70, 293]. To the author's knowledge, only one study has explored the test-retest reliability of force-time metrics obtained during different phases of the CMJ using soccer players [292]. The study involved a combination of pre- and post-Peak Height Velocity (PHV) youth soccer players, and a key observation was that most CMJ parameters calculated for the post-PHV group demonstrated acceptable absolute reliability with a CV < 10% (a typical cut-off for acceptable absolute reliability [59, 294]), but this was not the case for the pre-PHV group [292], which suggests that CMJ test-retest reliability improved with maturation.

Additionally, technique-intensive tests generally exhibit greater variability in results and require more pre-test practice to produce consistency, therefore, greater reliability might be seen from an athlete with more experience with a task (e.g., due to more years of practice) [36]. Professional athletes with a greater chronological age would generally coincide with having more experience with said tasks because of more seasons of testing [36]. Thus, it can be hypothesised that most CMJ force-time metrics reported for older (e.g., adult) soccer players would be reliable [292]. However, to the author's knowledge no study has explored the test-retest reliability of CMJ force-time metrics for adult soccer players to confirm this. Furthermore, a limitation of the study by Ruf et al. [292] was that while two CMJ trials were performed by the athletes, only the trial with the highest TOV was included in the statistical analyses. If force plate data collection procedures are repeated exactly [205], the reliability of a measure is determined by equipment error and biological variation [36]. We cannot know what an athlete's "true" test score is from a single test trial, so taking forward the average across two or more trials for statistical analyses is suggested as a more reliable approach as opposed to only taking the single "best" trial [68, 70, 291, 295]. Therefore, the test-retest reliability of CMJ force-time metrics obtained by the chronologically eldest youth soccer player groups (i.e., the U17 and U18 groups) may be better than what has been previously reported [292], should the average of multiple trials be considered.

The CMRJ test has been proposed as a potential alternative to the more traditional DJ test for the assessment of fast SSC capacity, because similarities have been reported in hip, knee, and ankle joint work between both tests [173, 176], but there are reported discrepancies between standardised box height and actual fall height in the DJ test [21] which would lead to erroneous measures of NMF. The CMRJ overcomes this issue in practice because a box is not needed to conduct the test, where the JH in the preliminary CMJ portion, which initiates the test and creates the fall height for the RJ portion, has demonstrated acceptable absolute and relative reliability [176]. Additionally, falling from a height in the RJ portion that is dictated by one's individual physical capacity may be considered fairer to individuals that may not be able to jump as high as a standardised box height in a DJ test (e.g., 40 cm). On the contrary, a comparison of NMF from force-time variables derived from the RJ portion may prove difficult in sports where body masses differ between positional groups (e.g., in rugby league) because of the interaction between body mass, fall height, touch-down velocity, landing momentum (body mass multiplied by touch-down velocity), and thus net braking impulse [296]. For example, McMahon et al. [40] reported that rugby league forwards were ~12 kg heavier on average than backs with a large effect (g = 1.34). Consequently, CMJ take-off momentum (which would equal RJ landing momentum in the CMRJ test) has been reported as significantly ($p < 0.01$) and largely (g = 1.01) greater for forwards over backs [296]. This would result in forwards being required to produce greater RJ portion net braking impulse than backs in the RJ portion and thus comparing NMF between positional groups in rugby league using the CMRJ test could prove difficult. Although produced by McMahon et al. [40, 296] for the CMJ test, a comparison of CMRJ performance between positional groups in rugby league is yet to be performed in literature.

Xu et al. [173, 176] identified acceptable absolute (CV <10%) and relative (ICC >0.75) reliability in metrics such as CMJ portion JH, countermovement depth, and time to take-off, and RJ portion JH and GCT. However, based on the 95% CI [297], relative and absolute reliability was not acceptable for CMJ time to take-off (lower bound 95% CI, ICC = 0.64) and RJ portion GCT (upper bound 95% CI, CV = 10.19%), respectively. Additionally, the authors stated that the recruited subjects (N = 33 sports science students with mixed sports backgrounds) had minimal experience with plyometric tasks [173, 176], thus suggesting these results may hold limited utility for informing the practice of professional athletes [176]. The limited familiarity with fast SSC tasks (i.e., plyometrics) would explain why Xu et al. [173, 176] reported average GCTs >300 ms for the DJ and CMRJ tests in both testing sessions, thus failing construct validity as an assessment of fast SSC capacity (i.e., GCT <250 ms [117, 158]). These studies were also limited in their metric selection, where kinetic measures (i.e., force and power measures) during any phase of the test were not reported in these studies [173, 176]. To the author's knowledge, no researchers have explored the test-retest reliability of force-time metrics obtained during different phases of the CMRJ test in soccer players using force plates. Therefore, the utility of this test and its measures to be utilised for monitoring acute changes in NMF (i.e., do the measures present acceptable test-retest reliability?) in soccer players is yet to be determined.

The most popular isometric assessment is the IMTP which is employed to evaluate maximal lower body "strength" [188-190]. It is considered safer, less fatiguing, quicker to perform, and more practically feasible than dynamic repetition maximum testing (e.g., the back squat) [187], particularly when evaluating large groups simultaneously (i.e., as generally seen in soccer). Peak force is the most reported IMTP metric [23], which has been related to the performance of various other physical tests, such as CMJ height (r = 0.82 [198]), SJ height (r = 0.87 [198]), 5 and 20 metre sprint speed (r = -0.57 and -0.69, respectively [199]), and COD speed and manoeuvrability in the T-Test (r = -0.85 [200]), 505 test (r = -0.79 [200]), and modified 505 test (r = -0.57 [199]), as a few examples. Peak force has demonstrated acceptable absolute and relative reliability in youth soccer players [189, 270], especially once athletes become more familiar with the task [270]. To the author's knowledge, the reliability of the IMTP has not yet been reported for professional soccer players in the EFL. Researchers have reported acceptable reliability in IMTP metrics such as relative peak force [270], force at 30 ms, 50 ms, 90 ms [189], 100 ms [189, 270], 150 ms, 200 ms, and 250 ms [189]. However, upon further investigation of these respective studies, only peak force [189, 270], relative peak force [270], and force at 250 ms demonstrated acceptable absolute and relative reliability based on the lower bound 95% CI [297]. Additionally, similar to the observed methodological limitations of the abovementioned study by Ruf et al. [292], Musham & Fitzpatrick [270] took forward only the IMTP trial with the highest peak force for statistical analysis, therefore, the reliability of IMTP metrics demonstrated in this study may have been underrepresented as opposed to if the average of multiple trials been taken forward for analysis [270]. Dos'Santos et al. [189] utilised a single, laboratory-grade, piezoelectric Kistler model 9286AA force platform, but recent developments in force-plate technology have introduced wireless and portable, strain-gauge, dual-force plate options which are much more practical for the applied setting. The reliability of IMTP metrics using HD Inc. hardware is yet to be reported. Consequently, determining the test-retest reliability of IMTP metrics in professional and youth soccer players using wireless and portable, strain-gauge, dual-force plate system and appropriate data analysis and statistical interpretation is warranted.

7.2 AIMS AND OBJECTIVES

Subsequent to the rise in popularity of force plate testing among S&C coaches in soccer [23, 161, 289], it is recommended that practitioners determine the reliability of tests and force-time metrics of interest within the specific environments, protocols, and cohorts used in practice [70]. Thus, it would be useful to identify the test-retest reliability of force-time metrics from tests of lower-body NMF such as the CMJ (slow SSC), DJ and CMRJ (fast SSC), and IMTP (isometric strength) in professional and youth soccer players, using a wireless and portable force plate system. An outline of the structure of this chapter consisting of three studies designed to evaluate two different cohorts (professional and youth soccer players) at two different times of the competitive season (pre- and in-season) has been illustrated in Figure 7.1. This information will be useful to both researchers and practitioners who currently, or plan to, monitor CMJ, DJ, CMRJ, and IMTP force-time characteristics of soccer players using recently developed wireless, portable, strain-gauge, dual-force plate systems. It was hypothesised that reliability would be better for propulsive- over countermovement-phase force-time metrics in VJs, better for the adult versus the youth soccer players in the pre-season period, and better in-season compared to pre-season, based on previous studies results [65, 68-70]. Additionally, based on previous findings [173, 176], it was hypothesised that the reliability of outcome measures during the CMJ portion of the CMRJ test would be acceptable and thus overcome the issues of variability in fall height previously demonstrated in the DJ test [21, 170, 171]. The study will conclude by proposing the most reliable measures within the context of absolute and relative reliability results and discuss the application of these measures in practice for professional and youth soccer players.

Study "A"

- **"PROFESSIONAL" soccer players in the "PRE-SEASON" period.**
  - Countermovement Jump ONLY.
- **Rationale**
  - (1) the absence of peer-reviewed test-retest reliability studies involving CMJ force-time metrics obtained by professional soccer players.
- **Aims**
  - Determine the test-retest reliability of a range of ratio, outcome, kinetic, and strategy metrics for the CMJ test in professional soccer players in the pre-season period.

Study "B"

- **"YOUTH" soccer players in the "PRE-SEASON" period.**
  - Countermovement Jump, Countermovement Rebound Jump, Drop Jump, and Isometric Mid-Thigh Pull Tests.
- **Rationale**
  - (1) limitations of previous data analysis procedures, e.g., not taking the average of 2-3 trials forward for VJ and IMTP analysis in studies in youth soccer.
  - (2) limitations in previous data collection procedures in studies utilising the CMRJ and DJ tests, e.g., utilising non-athlete populations and trials failing to be performed with a GCT under 250 ms.
  - (3) the absence of test-retest reliability studies involving CMRJ force-time metrics in youth soccer.
- **Aims**
  - Determine the test-retest reliability of a range of ratio, outcome, kinetic, and strategy metrics for the CMJ, CMRJ, DJ, and IMTP tests in youth soccer players in the pre-season period.

Study "C"

- **"YOUTH" Soccer players in the "IN-SEASON" period.**
  - Countermovement Jump and Countermovement Rebound Jump Tests.
- **Rationale**
- In addition to the rationale of "study b":
  - (1) the observation that CMJ test-retest reliability improved with developmental age (maturation).
  - (2) the observation that training status and experience with a task (e.g., from pre- to mid-season) may improve the reliability of test results in youth soccer players.
  - The in-season being typically when the monitoring of NMF would be performed in soccer due to congested training and fixture schedules.
- **Aims**
  - Determine the test-retest reliability of a range of ratio, outcome, kinetic, and strategy metrics for the CMJ and CMRJ tests in youth soccer players in the in-season period.

Figure 7.1. Illustration of the chapter's design, consisting of three separate studies.

7.3 MATERIALS AND METHODS

A test-retest repeated-measures design was employed for all studies in this chapter. All testing was held at the same location, at the same time of day, and exactly a week apart. Ethical approval was granted via the University of Salford ethics committee which adheres to the principles of the 2013 Declaration of Helsinki. A participant information sheet, consent form, and physical activity readiness questionnaire were provided to participants at the beginning of both testing sessions. Parental assent was sought for any participants under the age of eighteen years. Dataset samples have been categorised based on the population assessed (i.e., professional or youth) and the point of the season testing was conducted (i.e., pre- or in-season).

7.3.1 Subjects

An *a priori* sample size estimation was performed for this study [298-301] utilising an online reliability study sample size calculator [298]. Previous reliability studies have reported between session relative reliability (ICC) for common metrics such as CMJ JH (0.98) [173], DJ JH (0.95) [173], CMRJ RJ portion JH (0.93) [173], and IMTP peak force (0.98) [173]. The average relative reliability (ICC) from these measures equalled 0.96, which was utilised as the expected reliability in the sample size estimation. For a test-retest design with 2 sessions, minimum acceptable reliability (ICC) of 0.75 (based on the lower bound 95% CI), excepted reliability (ICC) 0.96, and an alpha level of 0.05, the required sample size was calculated as a minimum of 15 participants for a statistical power of 0.95 [298].

In study A), twenty-two professional male soccer players (age 25.4 ± 4.0 years, height 183.3 ± 6.0 cm, body mass 81.9 ± 9.0 kg) from a single EFL League 2 club performed three maximal-effort CMJs on the first and eighth day (i.e., 7-days apart) of the 2022-2023 pre-season training period. The EFL League Two is the fourth-highest division overall in English football and, therefore, the athletes tested in this study may be classified as tier 3 (i.e., highly trained/national level) participants [302].

In study B), eighteen male youth soccer players (age 16.4 ± 0.5 years, height 181.1 ± 7.3 cm, body mass 73 ± 7.7 kg) performed three maximal-effort CMJ, CMRJ, DJ, and IMTP trials, in a randomised order, on the first and eighth day (i.e., 7-days apart) of the 2022-2023 pre-season training period. All athletes were involved in a full-time EFL academy programme (category 4), which involved a minimum of 5 technical development focused field-based and 2 physical development focused gym-based sessions per week.

In study C), forty-three male youth soccer players (age 17.9 ± 0.9 years, height 181 ± 5.8 cm, body mass 72.5 ± 6.8 kg) performed three maximal-effort CMJs and three maximal-effort CMRJs, in a randomised order, on the first and eighth day (i.e., 7-days apart) of the 2021-2022 mid-season formative evaluation period. All athletes were involved in a full-time EFL academy programme (categories 2 and 4), which involved a minimum of 5 technical development focused field-based and 2 physical development focused gym-based sessions per week.

Both professional and youth soccer players had previous experience performing the CMJ and RJ in training and previous physical performance testing. Experience with the IMTP test was varied.

7.3.2 Procedures

A full description of data collection procedures for the CMJ, DJ, CMRJ, and IMTP tests can be found in Chapter 5 titled "General Methods".

7.3.3 Data Analysis

Data analysis was automatically performed after each trial via the HD Inc. proprietary software. In VJ tests, this proprietary software utilised forward dynamics to calculate a multitude of performance metrics relating to acceleration, velocity, and displacement [25]. Accordingly, the impulse-momentum theorem was utilised to calculate JH from TOV, where JH was calculated as:

$$TOV^2 / (2 \times g)$$

[230, 260].

Similar to recent reliability research [293], in this chapter metrics will be discussed based on the characterisations "outcome metrics", "kinetic metrics", and "strategy metrics". "Kinetic metrics" refers to measures associated with GRF production (e.g., peak force, average force, impulse, etc.). "Strategy metrics" refers to measures associated with the movement strategy performed from the onset of movement through to the point of take-off (e.g., time to take-off, GCT, etc.). "Outcome metrics" refers to any metrics from the point of take-off through the flight phase (e.g., TOV, JH, FT, etc.) [184, 293]. The weighing phase was determined as from the instant the trial is initiated (i.e., the moment the tester starts the test on the tablet) to the instant that the SD of vGRF is less than 25 N for ≥ 1 s for the CMJ and CMRJ [248, 249, 260] and IMTP [187] tests. Unlike the CMJ test [25], body weight is not determined in the first phase of the DJ test using the HD Inc. system [260]. Instead, body weight is sourced from a CMJ, CMRJ, or Weighing Protocol trial (Table 5.2) [260]. The box height of the trial was inputted into the tablet's proprietary software prior to the commencement of a DJ trial. Touch-down velocity was determined from this inputted box height and actual fall height was not determined via the proprietary software. Specific metric definitions, phase descriptions, and information regarding potential sources of error for each test can be found in Chapter 5 titled "General Methods".

7.3.4 Statistical Analyses

Statistical analyses were performed using a customized Microsoft Excel (version 16; Microsoft Corp., Redmond, WA, USA) spreadsheet and SPSS software (version 25; SPSS Inc., Chicago, IL, USA). The average of each subject's three CMJ, CMRJ, DJ, and IMTP trials (for each metric) on both testing occasions were calculated and taken forward for analysis. Three trials were utilised to account for the inherent variability (i.e., biological variability and measurement error [202]) in repeated measurements by the same subject around the mean value [303]. Consequently, as all measurements incorporate error, a single measurement should not be referred to as a "true score" but rather an "observed score" [202]. Furthermore, at least two measurements for each subject are required to estimate the within-subject variability [304], calculated via the within subject SD [303].

Absolute between-session reliability was assessed using Microsoft Excel (version 16; Microsoft Corp., Redmond, WA, USA). For every participant, the mean value from session 1 was subtracted from the mean value from session 2 to calculate the absolute difference for each metric [202, 303]. Then, the group mean estimate and SD of the absolute difference for each metric was calculated [202, 303], which is the most popular method in studies conducted with test-retest designs [202]. Calculating the average absolute difference and variability for a cohort and assuming it is the same for all athletes is a recommended approach because variability in scores (i.e., due to biological variability and measurement error) will differ between athletes regardless of magnitude of the score obtained [202, 303].

In practice, it is important to estimate and quantify the magnitude of measurement error of any single measurement [202]. This can be achieved by differentiating measurement error from the inherent total variability of the absolute difference [50]. The SEM method has been employed to do this in health science research [50, 305, 306], by isolating measurement error from the SD (i.e., total variability) of the absolute difference. The SEM was calculated as:

$$\text{SD of absolute difference} / \sqrt{2}$$

[50, 202, 305, 306].

Based on the assumption that observed scores follow a normal distribution around the mean, 95% of observed scores should lie within 2 SDs of the mean value [202], where the remaining 5% are equally scattered above and below these limits [304]. The difference between a subject's measurement and the true value would be expected to be less than 1.96 for 95% of observations [303]. Additionally, a value of absolute difference and variability may vary between samples (i.e., due to sampling distribution), therefore, the precision (i.e., “standard error”) of the sample mean must be considered [304]. The standard error (not to be confused with SEM) of the sample mean depends on both the SD and the sample size, calculated as:

$$\text{SD of absolute difference} / \sqrt{(\text{sample size})}$$

[304].

It has been suggested that the standard error is most useful when integrated into the method of calculating a CI [304]. Therefore, CIs were calculated with consideration for the 2 SD limit of 95% (1.96) [202] and standard error rationale [304], and were calculated as:

$$1.96 * (\text{SD of absolute difference} / \sqrt{(\text{sample size})})$$

[202, 304].

The CI was then utilised by adding it to the SEM to provide an upper bound 95% CI for the SEM. The SEM and upper-bound 95% CI of the SEM were also expressed as a percentage via the CV, which provides a ratio of measurement error in relation to the grand mean [307], by dividing them by the grand mean of sessions 1 and 2 and multiplying the value by 100 [202]. A CV of ≤10% has been used as an indicator of “acceptable” reliability in previous similar studies [59, 294]. Additionally, *ranges* of absolute reliability have been used with thresholds of <5%, 5-10%, and >10% corresponding to good, moderate, and poor reliability, respectively [308]. In this chapter, ≤5%, >5 to 10%, >10% to 15%, and >15% thresholds (based on the 95% CI of the CV% estimate) were considered to represent excellent, good, moderate, and poor reliability, respectively. “Acceptable” absolute reliability was deemed as those measures which represented excellent to good (i.e., ≤10%) reliability based on the upper bound 95% CI [297].

The MDC was also calculated to provide a measure of the minimum amount of change required for a value change to be likely greater than the estimated measurement error, and therefore considered “meaningful” [50]. It is traditionally based on the SEM and a degree of confidence (i.e., the upper-bound CI) in a test–retest reliability design [306]. Therefore, the upper-bound 95% CI of the SEM was utilised to produce the MDC, calculated as:

$$SEM + 95\%\ CI * \sqrt{2}$$

[202, 305].

The MDC was then also expressed as a percentage, by dividing it by the grand mean of sessions 1 and 2 and multiplying the value by 100 [305].

Relative between-session reliability was assessed using SPSS software (version 25; SPSS Inc., Chicago, IL, USA). A two-way mixed-effects model (average measures) ICC (absolute agreement definition), along with upper and lower 95% CIs, was used. In this chapter, values ≤0.5, >0.50 to 0.75, >0.75 to 0.90, and >0.90 (based on the lower bound 95% CI of the ICC estimate) were indicative of poor, moderate, good, and excellent relative reliability, respectively [59]. "Acceptable" relative reliability was also deemed as those measures which represented excellent to good (i.e., ≥0.75 based on the lower bound 95% CI) reliability [309]. Metrics were determined as "reliable" if they demonstrated acceptable absolute and relative reliability based on the 95% CI.

7.4 RESULTS

STUDY A

(PROFESSIONAL PRE-SEASON)

The descriptive information and reliability statistics for this sample can be found in Table 7.1.

7.4.1 Countermovement Jump

Twenty-eight CMJ metrics were reported in this study (Table 7.1). Acceptable absolute reliability was demonstrated for 14 CMJ metrics in professional soccer players in the pre-season period based on the CV% upper bound 95% CI (Table 7.1). Acceptable relative reliability was demonstrated for 16 CMJ metrics in professional soccer players in the pre-season period based on the ICC lower bound 95% CI (Table 7.1). Consequently, acceptable absolute and relative reliability was demonstrated for 13 out of the 28 included CMJ metrics, based on the 95% CIs, in professional soccer players in the pre-season period (Table 7.1).

Table 7.1. Descriptive and Reliability Statistics of the Countermovement Jump Test.

CMJ Metrics	Session 1		Session 2		Mean Difference	SD	SEM	SEM +95	CV %	CV +95	ICC	ICC -95	MDC	MDC %
	Mean	SD	Mean	SD										
mRSI (AU)	0.48	0.10	0.46	0.08	-0.02	0.06	0.04	0.07	9.20	14.64	0.87	0.69	0.10	20.61
FT:CT (AU)	0.73	0.13	0.71	0.11	-0.01	0.09	0.06	0.10	8.90	14.15	0.84	0.61	0.14	19.99
Jump Height (m)	0.38	0.05	0.37	0.05	-0.01	0.02	0.01	0.02	3.04	4.83	0.96	0.87	0.03	6.82
Flight Time (s)	0.58	0.04	0.57	0.03	-0.01	0.01	0.01	0.01	1.45	2.31	0.96	0.89	0.02	3.27
Jump Momentum (Kg*m/s)	222.37	23.38	220.38	24.93	-1.98	4.57	3.15	5.02	1.42	2.27	0.99	0.97	7.10	3.21
Takeoff Velocity (m/s)	2.72	0.18	2.69	0.17	-0.03	0.06	0.04	0.06	1.50	2.38	0.96	0.88	0.09	3.37
Time to Take-off (s)	0.83	0.14	0.83	0.12	0.00	0.10	0.07	0.11	8.55	13.60	0.82	0.57	0.16	19.18
Stiffness (N/m)	6464.89	1479.98	6631.66	2078.27	-166.77	1451.52	1002.78	1595.38	15.31	24.36	0.81	0.55	2256.21	34.46
Mean Propulsive Power (W)	2562.28	311.09	2523.76	347.37	-38.52	169.03	116.77	185.78	4.59	7.31	0.93	0.83	262.74	10.33
Peak Propulsive Power (W)	4306.80	480.70	4235.39	495.17	-71.41	184.77	127.65	203.08	2.99	4.75	0.96	0.90	287.20	6.72
Peak Velocity (m/s)	2.82	0.16	2.79	0.16	-0.03	0.06	0.04	0.06	1.40	2.23	0.96	0.88	0.09	3.16
Mean Propulsive Velocity (m/s)	1.67	0.10	1.66	0.10	-0.01	0.05	0.04	0.06	2.28	3.62	0.92	0.81	0.09	5.11
Net Impulse Ratio (AU)	2.06	0.40	2.05	0.45	-0.01	0.28	0.19	0.31	9.44	15.02	0.88	0.71	0.44	21.21
Mean Propulsive Force (N)	1699.79	167.16	1689.04	193.98	-10.75	95.56	66.02	105.03	3.90	6.20	0.93	0.83	148.53	8.77
Peak Propulsive Force (N)	2118.10	294.65	2133.55	342.32	15.45	188.77	130.41	207.48	6.13	9.76	0.91	0.78	293.42	13.80
Propulsive Phase (s)	0.25	0.03	0.26	0.04	0.00	0.02	0.02	0.03	6.45	10.26	0.89	0.74	0.04	14.50
Countermovement Depth (m)	0.33	0.05	0.33	0.06	0.00	0.04	0.03	0.04	7.96	12.67	0.88	0.70	0.06	17.94
Force at Min Displacement (N)	2082.39	313.29	2090.23	369.31	7.84	181.97	125.71	200.01	6.03	9.59	0.93	0.82	282.85	13.56
Braking RFD (N/s)	8751.47	3379.62	8951.45	4441.29	199.98	3134.80	2165.67	3445.50	24.47	38.93	0.82	0.56	4872.67	55.05
Mean Braking Power (W)	1267.02	313.45	1276.48	347.05	-9.46	183.13	126.51	201.28	9.95	15.83	0.92	0.81	284.65	22.38
Peak Braking Power (W)	1750.07	493.31	1759.49	521.34	-9.42	323.58	223.54	355.65	12.74	20.27	0.89	0.74	502.96	28.66
Mean Braking Velocity (m/s)	0.90	0.11	0.90	0.13	0.00	0.08	0.05	0.09	5.96	9.49	0.88	0.72	0.12	13.42
Net Braking Impulse (N.s)	112.29	22.38	113.25	25.39	0.96	10.72	7.41	11.79	6.57	10.45	0.95	0.88	16.67	14.78
Mean Braking Force (N)	1554.25	247.33	1562.38	287.96	8.13	166.46	115.00	182.96	7.38	11.74	0.90	0.75	258.74	16.60
Peak Braking Force (N)	2094.53	319.05	2097.28	372.18	2.75	180.48	14.09	22.41	5.95	9.46	0.93	0.83	31.70	1.51
Braking Phase (s)	0.16	0.04	0.16	0.04	0.00	0.03	0.02	0.03	12.82	20.40	0.82	0.57	0.05	28.70
Unweighting Phase (s)	0.41	0.11	0.41	0.10	0.00	0.09	0.06	0.10	15.63	24.87	0.75	0.37	0.15	35.51
Body Weight (N)	803.47	88.78	805.67	90.06	2.19	8.30	5.73	9.12	0.71	1.13	1.00	1.00	12.90	1.60

Key: CMJ, countermovement jump; SD, standard deviation; SEM, standard error of measurement; CV, coefficient of variation; ICC, intraclass correlation coefficient; MDC, minimal detectable change; mRSI, modified reactive strength index; FT:CT, flight time contraction time ratio; min, minimum; RFD, rate of force development; AU, arbitrary unit; m, metres; s, seconds; Kg, kilograms; N, Newtons; W, watts; dark green cell shading, excellent reliability; bright green cell shading, good reliability; orange cell shading, moderate reliability; red cell shading, poor reliability.

STUDY B

(YOUTH PRE-SEASON)

The descriptive and reliability statistics for this sample can be found in Tables 7.2-7.6.

7.4.2 Countermovement Jump

Twenty-six CMJ metrics were reported in this study (Table 7.2). Acceptable absolute reliability was demonstrated for 11 CMJ metrics in youth soccer players in the pre-season period, based on the CV% upper bound 95% CI (Table 7.2). Acceptable relative reliability was demonstrated for seven CMJ metrics in youth soccer players in the pre-season period, based on the ICC lower bound 95% CI (Table 7.2). Consequently, acceptable absolute and relative reliability was demonstrated for five out of the 27 included CMJ metrics, based on the 95% CIs, in youth soccer players in the pre-season period (Table 7.2).

Table 7.2. Descriptive and Reliability Statistics of Countermovement Jump Test Metrics.

CMJ Metrics	Session 1		Session 2		Mean Difference	SD	SEM	SEM +95	CV %	CV +95	ICC	ICC -95	MDC	MDC %
	Mean	SD	Mean	SD										
mRSI (AU)	0.58	0.10	0.57	0.12	-0.01	0.10	0.07	0.11	12.02	19.87	0.75	0.32	0.16	28.10
FT:CT (AU)	0.93	0.16	0.94	0.17	0.00	0.16	0.11	0.19	12.12	20.04	0.69	0.13	0.26	28.34
Jump Height (m)	0.33	0.04	0.31	0.04	-0.02	0.03	0.02	0.03	6.40	10.58	0.83	0.52	0.05	14.96
Flight Time (s)	0.52	0.04	0.51	0.03	-0.01	0.02	0.02	0.03	3.17	5.24	0.81	0.44	0.04	7.41
Jump Momentum (Kg*m/s)	183.65	21.93	179.15	23.07	-4.50	8.47	5.82	9.63	3.21	5.31	0.96	0.86	13.62	7.51
Takeoff Velocity (m/s)	2.52	0.17	2.46	0.15	-0.06	0.12	0.08	0.13	3.25	5.37	0.82	0.51	0.19	7.59
Time to Take-off (s)	0.58	0.10	0.57	0.11	-0.02	0.11	0.08	0.13	13.27	21.93	0.62	0.20	0.18	31.02
Stiffness (N/m)	12568.80	6907.46	13806.97	7157.31	-1238.17	4962.52	3410.16	5638.14	25.86	42.75	0.86	0.63	7973.53	60.46
Mean Propulsive Power (W)	2471.89	344.53	2444.15	441.52	-27.74	198.17	136.18	225.15	5.54	9.16	0.94	0.83	318.41	12.95
Peak Propulsive Power (W)	4046.35	520.53	4075.04	680.11	28.69	270.24	185.71	307.03	4.57	7.56	0.95	0.87	434.21	10.69
Peak Velocity (m/s)	2.63	0.16	2.58	0.14	-0.05	0.11	0.08	0.13	2.91	4.81	0.83	0.54	0.18	6.80
Mean Propulsive Velocity (m/s)	1.65	0.10	1.62	0.12	-0.03	0.08	0.05	0.09	3.16	5.22	0.87	0.65	0.12	7.38
Net Impulse Ratio (AU)	2.03	0.25	2.10	0.34	0.07	0.20	0.14	0.23	6.80	11.25	0.86	0.64	0.33	15.91
Mean Propulsive Force (N)	1745.52	223.63	1758.85	270.66	13.32	122.99	84.52	139.73	4.82	7.97	0.94	0.83	197.61	11.28
Peak Propulsive Force (N)	2390.30	521.00	2493.46	648.07	103.17	333.53	229.19	378.93	9.39	15.52	0.91	0.76	535.89	21.95
Propulsive Phase (s)	0.19	0.04	0.18	0.04	-0.01	0.02	0.02	0.03	9.33	15.43	0.89	0.71	0.04	21.82
Countermovement Depth (m)	0.21	0.05	0.19	0.05	0.02	0.04	0.03	0.04	12.77	21.11	0.81	0.50	0.06	29.85
Braking RFD (N/s)	19381.56	17141.50	22174.93	18498.29	2793.37	11364.32	7809.38	12911.51	37.58	62.14	0.89	0.70	18259.64	87.88
Mean Braking Power (W)	1231.97	270.95	1217.31	403.58	14.66	228.65	157.12	259.78	12.83	21.21	0.88	0.68	367.38	30.00
Peak Braking Power (W)	1866.25	562.47	1824.90	710.34	41.35	374.21	257.15	425.16	13.93	23.04	0.91	0.76	601.27	32.58
Mean Braking Velocity (m/s)	0.81	0.07	0.78	0.10	0.03	0.07	0.05	0.08	5.97	9.87	0.78	0.42	0.11	13.95
Net Braking Impulse (N.s)	92.36	15.40	87.80	16.64	-4.56	7.44	5.11	8.45	5.68	9.38	0.93	0.75	11.96	13.27
Mean Braking Force (N)	1712.49	365.74	1751.68	487.91	39.19	301.40	207.12	342.43	11.96	19.77	0.87	0.64	484.27	27.96
Peak Braking Force (N)	2360.57	577.77	2475.61	860.57	115.04	503.95	346.31	572.56	14.32	23.68	0.87	0.65	809.73	33.49
Braking Phase (s)	0.10	0.03	0.10	0.04	0.00	0.03	0.02	0.03	18.61	30.77	0.86	0.62	0.04	43.52
Body Weight (N)	715.66	75.81	713.87	74.06	-1.78	7.81	5.37	8.87	0.75	1.24	1.00	0.99	12.55	1.76

Key: CMJ, countermovement; SD, standard deviation; SEM, standard error of measurement; CV, coefficient of variation; ICC, intraclass correlation coefficient; MDC, minimal detectable change; mRSI, modified reactive strength index; FT:CT, flight time contraction time ratio; min, minimum; RFD, rate of force development; AU, arbitrary unit; m, metres; s, seconds; Kg, kilograms; N, Newtons; W, watts; dark green cell shading, excellent reliability; bright green cell shading, good reliability; orange cell shading, moderate reliability; red cell shading, poor reliability.

7.4.3 Countermovement Rebound Jump

Thirty-six CMRJ metrics were reported in this study, which included 18 metrics calculated during the CMJ portion (including body weight; Table 7.3), and 18 metrics calculated during the RJ portion of the test (Table 7.4).

7.4.3.1 CMJ Portion

Acceptable absolute reliability was demonstrated for five CMJ portion metrics in youth soccer players in the pre-season period, based on the CV% upper bound 95% CI (Table 7.3). Acceptable relative reliability was demonstrated for 10 CMJ portion metrics in youth soccer players in the pre-season period, based on the ICC lower bound 95% CI (Table 7.3). Consequently, acceptable absolute and relative reliability was demonstrated for five out the 19 included CMJ portion metrics, based on the 95% CIs, in youth soccer players in the pre-season period (Table 7.3).

7.4.3.2 RJ Portion

Acceptable absolute reliability was demonstrated for seven RJ portion metrics in youth soccer players in the pre-season period, based on the CV% upper bound 95% CI (Table 7.4). Acceptable relative reliability was demonstrated for two RJ portion metrics in youth soccer players in the pre-season period, based on the ICC lower bound 95% CI (Table 7.4). Consequently, acceptable absolute and relative reliability was demonstrated for only one out of the 19 included RJ portion metrics, based on the 95% CIs, in youth soccer players in the pre-season period, which was net braking impulse (Table 7.4).

Table 7.3. Descriptive and Reliability Statistics of Countermovement Rebound Jump Test Metrics (Countermovement Jump Portion).

CMJ Portion Metrics	Session 1		Session 2		Mean	SD	SEM	SEM +95	CV %	CV +95	ICC	ICC -95	MDC	MDC %
	Mean	SD	Mean	SD	Difference									
mRSI (AU)	0.58	0.11	0.58	0.13	0.00	0.07	0.05	0.08	8.86	14.65	0.90	0.72	0.12	20.72
FT:CT (AU)	0.98	0.18	1.01	0.19	0.03	0.10	0.07	0.11	6.84	11.31	0.92	0.79	0.16	15.99
Jump Height (m)	0.30	0.05	0.29	0.04	-0.02	0.03	0.02	0.04	7.45	12.32	0.85	0.57	0.05	17.42
Jump Momentum (Kg*m/s)	177.53	23.99	172.30	23.10	-5.24	9.90	6.80	11.25	3.89	6.43	0.94	0.83	15.91	9.10
Time to Take-off (s)	0.54	0.10	0.51	0.10	-0.03	0.06	0.04	0.06	7.28	12.04	0.89	0.70	0.09	17.03
Mean Propulsive Power (W)	2522.05	412.32	2482.42	427.06	-39.63	187.40	128.78	212.91	5.15	8.51	0.95	0.86	301.10	12.03
Peak Propulsive Power (W)	4149.21	647.29	4082.52	682.47	-66.69	232.57	159.82	264.24	3.88	6.42	0.97	0.92	373.69	9.08
Net Impulse Ratio (AU)	2.14	0.35	2.18	0.32	0.04	0.22	0.15	0.25	6.98	11.54	0.88	0.69	0.35	16.32
Mean Propulsive Force (N)	1826.32	286.54	1842.52	302.15	16.20	108.85	74.80	123.67	4.08	6.74	0.97	0.91	174.89	9.53
Peak Propulsive Force (N)	2659.98	693.02	2764.63	796.02	104.65	392.06	269.42	445.43	9.93	16.42	0.93	0.80	629.94	23.23
Countermovement Depth (m)	0.18	0.05	0.17	0.05	0.02	0.03	0.02	0.04	13.02	21.53	0.87	0.63	0.05	30.44
Braking RFD (N/s)	26181.70	19882.89	29226.22	22996.40	3044.52	12989.02	8925.85	14757.41	32.22	53.27	0.90	0.74	20870.13	75.33
Mean Braking Power (W)	1211.50	298.48	1161.39	331.04	50.11	220.90	151.80	250.97	12.79	21.15	0.86	0.63	354.93	29.92
Peak Braking Power (W)	1780.53	619.26	1651.47	527.42	129.06	481.06	330.58	546.55	19.26	31.85	0.79	0.44	772.94	45.04
Net Braking Impulse (N.s)	86.22	18.47	81.14	14.01	-5.09	10.37	7.12	11.78	8.51	14.07	0.87	0.64	16.66	19.90
Mean Braking Force (N)	1782.78	335.87	1787.79	446.23	5.02	209.13	143.71	237.60	8.05	13.31	0.93	0.81	336.02	18.82
Peak Braking Force (N)	2614.87	703.99	2634.94	857.78	20.07	351.44	241.51	399.29	9.20	15.21	0.95	0.87	564.68	21.51
Body Weight (N)	715.41	75.72	713.36	74.14	-2.05	7.83	5.38	8.90	0.75	1.25	1.00	0.99	12.58	1.76

Key: CMJ, countermovement jump; SD, standard deviation; SEM, standard error of measurement; CV, coefficient of variation; ICC, intraclass correlation coefficient; MDC, minimal detectable change; mRSI, modified reactive strength index; FT:CT, flight time contraction time ratio; min, minimum; RFD, rate of force development; AU, arbitrary unit; m, metres; s, seconds; Kg, kilograms; N, Newtons; W, watts; dark green cell shading, excellent reliability; bright green cell shading, good reliability; orange cell shading, moderate reliability; red cell shading, poor reliability.

Table 7.4. Descriptive and Reliability Statistics of Countermovement Rebound Jump Test Metrics (Rebound Jump Portion).

RJ Portion Metrics	Session 1		Session 2		Mean Difference	SD	SEM	SEM +95	CV %	CV +95	ICC	ICC -95	MDC	MDC %
	Mean	SD	Mean	SD										
RSI (AU)	1.60	0.26	1.46	0.26	-0.15	0.20	0.14	0.23	8.98	14.84	0.76	0.25	0.32	20.99
FT:CT (AU)	2.50	0.29	2.37	0.33	-0.12	0.24	0.16	0.27	6.71	11.10	0.80	0.44	0.38	15.69
Jump Height (m)	0.34	0.05	0.31	0.04	-0.02	0.04	0.03	0.05	8.94	14.78	0.66	0.13	0.07	20.90
Flight Time (s)	5.22	0.33	5.07	0.31	-0.15	0.32	21.81	36.06	4.24	7.00	0.65	0.12	51.00	990.54
Jump Momentum (Kg*m/s)	186.18	19.98	179.33	21.01	-6.85	12.26	8.42	13.93	4.61	7.62	0.88	0.64	19.70	10.78
Ground Contact Time (s)	0.21	0.02	0.22	0.03	0.01	0.02	0.02	0.03	7.16	11.83	0.78	0.41	0.04	16.74
Stiffness (N/m)	43484.53	17915.60	43648.06	25382.26	-163.53	20094.96	13808.94	22830.78	31.70	52.40	0.75	0.31	32287.60	74.11
Mean Propulsive Power (W)	3418.98	418.67	3195.25	498.66	-223.73	282.05	193.82	320.45	5.86	9.69	0.85	0.39	453.19	13.70
Peak Propulsive Power (W)	5706.22	707.10	5346.03	848.19	-360.18	478.41	328.76	543.54	5.95	9.84	0.85	0.44	768.69	13.91
Net Impulse Ratio (AU)	1.01	0.07	0.99	0.07	-0.01	0.04	0.03	0.05	2.90	4.79	0.90	0.73	0.07	6.78
Mean Propulsive Force (N)	2346.22	245.07	2252.06	319.69	-94.15	131.12	90.10	148.97	3.92	6.48	0.92	0.68	210.67	9.16
Peak Propulsive Force (N)	4002.89	466.59	3881.44	701.16	-121.44	378.70	260.24	430.26	6.60	10.91	0.88	0.69	608.48	15.44
Braking Depth (m)	0.11	0.03	0.11	0.03	0.00	0.02	0.01	0.02	13.54	22.38	0.82	0.50	0.03	31.65
Mean Braking Power (W)	3837.70	645.56	3597.78	526.76	239.92	403.06	276.98	457.93	7.45	12.32	0.83	0.50	647.62	17.42
Peak Braking Power (W)	7458.40	1948.11	7291.33	2050.21	167.08	1074.19	738.17	1220.44	10.01	16.50	0.93	0.80	1725.96	23.40
Net Braking Impulse (N.s)	185.25	23.92	180.22	23.72	-5.03	9.13	6.27	10.37	3.43	5.68	0.95	0.85	14.67	8.03
Mean Braking Force (N)	2702.87	372.10	2602.77	375.84	-100.09	264.34	181.65	300.33	6.85	11.32	0.85	0.60	424.73	16.01
Peak Braking Force (N)	4616.19	663.94	4523.72	811.97	-92.46	566.58	389.35	643.72	8.52	14.09	0.83	0.56	910.36	19.92

Key: RJ, rebound jump; SD, standard deviation; SEM, standard error of measurement; CV, coefficient of variation; ICC, intraclass correlation coefficient; MDC, minimal detectable change; RSI, reactive strength index; FT:CT, flight time contraction time ratio; min, minimum; RFD, rate of force development; AU, arbitrary unit; m, metres; s, seconds; Kg, kilograms; N, Newtons; W, watts; dark green cell shading, excellent reliability; bright green cell shading, good reliability; orange cell shading, moderate reliability; red cell shading, poor reliability.

7.4.4 Drop Jump

Twenty-one DJ metrics were reported in this study (Table 7.5). Acceptable absolute reliability was demonstrated for four DJ metrics in youth soccer players in the pre-season period, based on the CV% upper bound 95% CI, which included net braking impulse, body weight, FT, and mean propulsive force (Table 7.5). Acceptable relative reliability was demonstrated for two DJ metrics in youth soccer players in the pre-season period, based on the ICC lower bound 95% CI, which were net braking impulse and body weight (Table 7.5). Consequently, acceptable absolute and relative reliability was demonstrated for only two out of the 21 included DJ metrics, based on the 95% CIs, in youth soccer players in the pre-season period (Table 7.5), which were net braking impulse and body weight (Table 7.5).

Table 7.5. Descriptive and Reliability Statistics of Drop Jump Test Metrics.

DJ Metrics	Session 1		Session 2		Mean Difference	SD	SEM	SEM +95	CV %	CV +95	ICC	ICC -95	MDC	MDC %
	Mean	SD	Mean	SD										
RSI (AU)	1.72	0.43	1.41	0.31	-0.30	0.32	0.22	0.36	13.28	21.96	0.66	-0.09	0.51	32.61
FT:CT (AU)	2.41	0.23	2.44	0.29	0.03	0.27	0.19	0.31	7.77	12.85	0.65	0.00	0.44	18.05
Jump Height (m)	0.37	0.11	0.29	0.06	-0.08	0.08	0.05	0.09	14.77	24.42	0.60	-0.21	0.12	36.75
Flight Time (s)	0.51	0.04	0.49	0.04	-0.02	0.03	0.02	0.03	3.61	5.96	0.80	0.31	0.04	8.43
Jump Momentum (Kg*m/s)	185.31	23.57	167.88	20.39	-17.43	17.44	11.96	19.78	6.64	10.98	0.69	-0.08	27.97	15.84
Takeoff Velocity (m/s)	2.67	0.39	2.36	0.24	-0.31	0.27	0.19	0.31	7.32	12.10	0.61	-0.20	0.44	17.52
Peak Velocity (m/s)	3.13	0.92	2.57	0.56	-0.56	0.77	0.53	0.88	17.31	28.62	0.56	-0.11	1.24	43.58
Ground Contact Time (s)	0.21	0.02	0.20	0.02	-0.01	0.02	0.02	0.03	7.55	12.49	0.44	-0.38	0.04	17.79
Propulsive Phase (s)	0.12	0.01	0.11	0.01	-0.01	0.01	0.01	0.02	8.22	13.60	0.61	0.02	0.02	19.54
Mean Propulsive Power (W)	3365.06	525.24	2943.14	414.17	-421.92	402.21	275.91	456.18	8.54	14.11	0.63	-0.16	645.13	20.45
Peak Propulsive Power (W)	5600.88	829.94	4949.41	699.37	-651.47	669.94	459.58	759.83	8.53	14.10	0.63	-0.12	1074.57	20.37
Net Impulse Ratio (AU)	1.10	0.16	0.97	0.10	-0.13	0.11	0.08	0.13	7.25	11.99	0.62	-0.20	0.18	17.37
Mean Propulsive Force (N)	2234.28	223.77	2185.84	255.01	-48.44	165.24	113.35	187.41	5.12	8.47	0.86	0.63	265.04	11.99
Peak Propulsive Force (N)	3583.86	395.12	3618.06	541.49	34.20	400.21	274.54	453.91	7.63	12.62	0.79	0.42	641.93	17.83
Braking Phase (s)	0.09	0.01	0.09	0.01	0.00	0.01	0.01	0.01	9.20	15.21	0.64	0.02	0.02	21.42
Mean Braking Power (W)	3347.86	441.36	3516.53	512.75	-168.68	419.26	287.61	475.52	8.38	13.86	0.74	0.33	672.48	19.59
Peak Braking Power (W)	6791.78	1190.35	7293.10	1446.14	-501.32	799.62	548.53	906.91	7.65	12.65	0.87	0.57	1282.56	18.21
Net Braking Impulse (N.s)	169.41	21.34	172.64	20.29	3.24	4.06	2.79	4.61	1.63	2.70	0.99	0.92	6.52	3.81
Mean Braking Force (N)	2527.38	344.15	2672.04	409.54	144.67	315.40	216.36	357.72	8.31	13.73	0.77	0.37	505.89	19.46
Peak Braking Force (N)	4156.61	643.14	4457.88	899.95	301.27	666.66	457.33	756.12	10.52	17.39	0.75	0.34	1069.31	24.83
Body Weight (N)	687.73	86.43	701.28	81.73	13.56	17.05	11.70	19.34	1.69	2.79	0.98	0.91	27.36	3.94

Key: CMJ, countermovement; SD, standard deviation; SEM, standard error of measurement; CV, coefficient of variation; ICC, intraclass correlation coefficient; MDC, minimal detectable change; mRSI, modified reactive strength index; FT:CT, flight time contraction time ratio; min, minimum; RFD, rate of force development; AU, arbitrary unit; m, metres; s, seconds; Kg, kilograms; N, Newtons; W, watts; dark green cell shading, excellent reliability; bright green cell shading, good reliability; orange cell shading, moderate reliability; red cell shading, poor reliability.

7.4.5 Isometric Mid-Thigh Pull

Twelve IMTP metrics were reported in this study (Table 7.6). Acceptable absolute reliability was demonstrated for only one IMTP metric in youth soccer players in the pre-season period, based on the CV% upper bound 95% CI, which was peak force (Table 7.6). Acceptable relative reliability was demonstrated for none of the included IMTP metrics in youth soccer players in the pre-season period, based on the ICC lower bound 95% CI (Table 7.6). Consequently, acceptable absolute and relative reliability was demonstrated for none of the 12 included IMTP metrics, based on the 95% CIs, in youth soccer players in the pre-season period (Table 7.6).

Table 7.6. Descriptive and Reliability Statistics of Isometric Mid-Thigh Pull Test Metrics.

IMTP Metrics	Session 1		Session 2		Mean Difference	SD	SEM	SEM +95	CV %	CV +95	ICC	ICC -95	MDC	MDC %
	Mean	SD	Mean	SD										
Time to Peak Force (s)	2.74	0.57	3.08	0.76	0.34	0.85	0.58	0.93	20.06	31.91	0.32	-0.65	1.31	45.12
Peak Force (N)	2565.10	312.23	2747.24	313.33	182.14	242.79	166.55	264.98	6.27	9.98	0.76	0.20	374.74	14.11
RFD 0-250 ms (N/s)	4582.82	770.06	4636.55	862.82	53.73	1003.53	688.41	1095.24	14.93	23.76	0.41	-0.73	1548.91	33.60
Force at 250 ms (N)	1969.61	296.67	1969.06	296.87	-0.55	269.67	184.99	294.32	9.39	14.94	0.75	0.29	416.23	21.14
Force at 200 ms (N)	1868.00	317.62	1857.94	326.58	-10.06	297.12	203.82	324.27	10.94	17.41	0.74	0.27	458.59	24.62
RFD 0-150 ms (N/s)	5330.07	1422.19	5087.32	1460.09	-242.75	1536.19	1053.82	1676.59	20.23	32.19	0.61	-0.09	2371.05	45.52
Force at 150 ms (N)	1623.41	306.55	1573.02	312.72	-50.39	246.13	168.85	268.63	10.56	16.81	0.82	0.50	379.90	23.77
RFD 0-100 ms (N/s)	5103.92	1932.53	4809.02	1813.42	-294.90	1897.22	1301.48	2070.61	26.26	41.78	0.66	0.06	2928.28	59.08
Force at 100 ms (N)	1334.29	274.65	1290.82	283.73	-43.47	204.74	140.45	223.45	10.70	17.02	0.85	0.58	316.01	24.08
RFD 0-50 ms (N/s)	6564.31	3134.32	5880.78	2212.98	-683.53	2809.21	1927.10	3065.94	30.97	49.27	0.63	0.01	4335.90	69.68
Force at 50 ms (N)	1152.12	206.06	1103.96	201.87	-48.16	140.67	96.50	153.53	8.55	13.61	0.86	0.62	217.12	19.25
Force at 0 ms (N)	823.90	157.75	809.92	142.64	-13.98	90.15	61.84	98.39	7.57	12.04	0.90	0.74	139.14	17.03

Key: CMJ, countermovement; SD, standard deviation; SEM, standard error of measurement; CV, coefficient of variation; ICC, intraclass correlation coefficient; MDC, minimal detectable change; mRSI, modified reactive strength index; FT:CT, flight time contraction time ratio; min, minimum; RFD, rate of force development; AU, arbitrary unit; m, metres; s, seconds; Kg, kilograms; N, Newtons; W, watts; dark green cell shading, excellent reliability; bright green cell shading, good reliability; orange cell shading, moderate reliability; red cell shading, poor reliability.

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The descriptive and reliability statistics for this sample can be found in Tables 7.7-7.9.

7.4.6 Countermovement Jump

Twenty-five CMJ metrics were reported in this study (Table 7.7). Acceptable absolute reliability was demonstrated for 15 CMJ metrics in youth soccer players in the in-season period, based on the CV% upper bound 95% CI (Table 7.7). Acceptable relative reliability was demonstrated for 20 CMJ metrics in youth soccer players in the in-season period, based on the ICC lower bound 95% CI (Table 7.7). Consequently, youth soccer players in the in-season period demonstrated acceptable absolute and relative reliability for 15 out of the 25 included CMJ metrics, based on the 95% CIs (Table 7.7).

Table 7.7. Descriptive and Reliability Statistics of Countermovement Jump Test Metrics.

CMJ Metrics	Session 1		Session 2		Mean	SD	SEM	SEM +95	CV	CV +95	ICC	ICC -95	MDC	MDC %
	Mean	SD	Mean	SD	Difference									
mRSI (AU)	0.54	0.10	0.51	0.10	0.03	0.08	0.05	0.08	10.20	14.52	0.83	0.67	0.11	20.53
FT:CT (AU)	0.84	0.15	0.81	0.13	0.03	0.11	0.08	0.12	9.89	14.07	0.79	0.61	0.16	19.90
Jump Height (m)	0.34	0.04	0.34	0.04	0.00	0.02	0.01	0.02	4.25	6.05	0.92	0.85	0.03	8.55
Flight Time (s)	0.54	0.03	0.54	0.03	0.00	0.02	0.01	0.02	2.36	3.36	0.90	0.81	0.03	4.75
Jump Momentum (Kg*m/s)	186.22	18.88	186.50	17.55	0.28	5.81	4.11	5.84	2.20	3.14	0.97	0.95	8.26	4.43
Takeoff Velocity (m/s)	2.59	0.14	2.58	0.14	0.02	0.08	0.05	0.08	2.13	3.02	0.92	0.85	0.11	4.28
Time to Take-off (s)	0.66	0.10	0.69	0.09	0.02	0.08	0.06	0.08	8.31	11.82	0.78	0.59	0.11	16.71
Mean Propulsive Power (W)	2365.86	387.05	2333.61	370.36	32.25	154.95	109.57	155.89	4.66	6.63	0.96	0.92	220.45	9.38
Peak Propulsive Power (W)	3931.68	554.83	3889.55	542.30	42.13	220.55	155.95	221.87	3.99	5.67	0.96	0.92	313.78	8.02
Peak Velocity (m/s)	2.69	0.13	2.68	0.13	0.02	0.08	0.05	0.08	2.04	2.90	0.90	0.82	0.11	4.10
Mean Propulsive Velocity (m/s)	1.64	0.10	1.62	0.10	0.02	0.06	0.04	0.06	2.45	3.49	0.91	0.83	0.08	4.93
Net Impulse Ratio (AU)	2.08	0.30	2.06	0.28	0.01	0.16	0.12	0.17	5.63	8.01	0.91	0.84	0.23	11.33
Mean Propulsive Force (N)	1638.70	237.93	1627.84	225.77	10.86	85.28	60.31	85.80	3.69	5.25	0.97	0.94	121.33	7.43
Peak Propulsive Force (N)	2122.06	445.95	2081.37	434.26	40.69	188.49	133.28	189.62	6.34	9.02	0.95	0.91	268.17	12.76
Propulsive Phase Time (s)	0.21	0.04	0.21	0.04	0.00	0.02	0.01	0.02	5.49	7.82	0.94	0.89	0.02	11.05
Countermovement Depth (m)	0.25	0.06	0.25	0.05	0.00	0.02	0.02	0.02	6.79	9.65	0.95	0.91	0.03	13.65
Braking RFD (N/s)	12782.88	9260.99	11803.97	9215.37	978.91	4778.39	3378.83	4807.08	27.48	39.10	0.93	0.87	6798.24	55.30
Mean Braking Power (W)	1125.14	283.33	1098.64	234.59	26.50	166.26	117.56	167.26	10.57	15.04	0.89	0.79	236.54	21.27
Peak Braking Power (W)	1607.32	482.33	1555.53	389.97	51.80	329.42	232.93	331.40	14.73	20.96	0.84	0.70	468.67	29.64
Net Braking Impulse (N.s)	92.27	16.52	92.57	14.27	0.30	7.21	5.10	7.26	5.52	7.85	0.94	0.90	10.26	11.10
Mean Braking Force (N)	1506.30	325.20	1478.20	272.01	28.10	172.60	122.04	173.63	8.18	11.64	0.91	0.83	245.55	16.46
Peak Braking Force (N)	2063.22	489.34	2019.36	477.96	43.86	238.64	168.74	240.07	8.27	11.76	0.94	0.88	339.51	16.63
Braking Phase Time (s)	0.13	0.04	0.13	0.03	0.00	0.02	0.01	0.02	9.57	13.61	0.93	0.87	0.02	19.25
Unweighting Phase Time (s)	0.33	0.06	0.34	0.06	0.01	0.06	0.04	0.06	12.83	18.26	0.67	0.41	0.09	25.82
Body Weight (N)	704.56	66.18	710.97	66.28	6.41	6.81	4.81	6.85	0.68	0.97	1.00	0.97	9.69	1.37

Key: SD, standard deviation; SEM, standard error of measurement; CV, coefficient of variation; ICC, intraclass correlation coefficient; MDC, minimal detectable change; mRSI, modified reactive strength index; FT:CT, flight time contraction time ratio; min, minimum; RFD, rate of force development; AU, arbitrary unit; m, metres; s, seconds; Kg, kilograms; N, Newtons; W, watts; dark green cell shading, excellent reliability; bright green cell shading, good reliability; orange cell shading, moderate reliability; red cell shading, poor reliability.

7.4.7 Countermovement Rebound Jump

Thirty-eight CMRJ metrics were reported in this study, which included nineteen CMJ portion metrics (Table 7.8) and nineteen RJ portion metrics (Table 7.9).

7.4.7.1 CMJ Portion

Acceptable absolute reliability was demonstrated for 11 CMJ portion metrics in youth soccer players in the in-season period, based on the CV% upper bound 95% CI (Table 7.8). Acceptable relative reliability was demonstrated for 17 CMJ portion metrics in youth soccer players in the in-season period, based on the ICC lower bound 95% CI (Table 7.8). Consequently, youth soccer players in the in-season period demonstrated acceptable absolute and relative reliability for 11 out of the 19 included CMJ portion metrics, based on the 95% CIs (Table 7.8).

7.4.7.2 RJ Portion

Acceptable absolute reliability was demonstrated for 6 RJ portion metrics in youth soccer players in the in-season period, based on the CV% upper bound 95% CI (Table 7.9). Acceptable relative reliability was demonstrated for 16 RJ portion metrics in youth soccer players in the in-season period, based on the ICC lower bound 95% CI (Table 7.9). Consequently, youth soccer players in the in-season period demonstrated acceptable absolute and relative reliability for five out of the 19 included RJ portion metrics, based on the 95% CIs (Table 7.9).

Table 7.8. Descriptive and Reliability Statistics of the Countermovement Rebound Jump Test (Countermovement Jump Portion).

CMJ Portion Metrics	Session 1		Session 2		Mean Difference	SD	SEM	SEM +95	CV	CV +95	ICC	ICC -95	MDC	MDC %
	Mean	SD	Mean	SD										
mRSI (AU)	0.54	0.11	0.54	0.12	0.01	0.06	0.04	0.06	7.44	10.59	0.93	0.88	0.08	14.97
FT:CT (AU)	0.88	0.15	0.86	0.16	0.02	0.08	0.06	0.08	6.61	9.41	0.93	0.86	0.12	13.31
Jump Height (m)	0.32	0.04	0.32	0.04	0.01	0.03	0.02	0.03	5.56	7.90	0.87	0.75	0.04	11.18
Jump Momentum (Kg*m/s)	178.55	18.20	180.87	17.12	2.31	7.36	5.21	7.41	2.90	4.12	0.95	0.91	10.48	5.83
Takeoff Velocity (m/s)	2.49	0.16	2.51	0.14	0.03	0.10	0.07	0.10	2.82	4.01	0.87	0.76	0.14	5.67
Time to Take-off (s)	0.60	0.09	0.62	0.10	0.02	0.07	0.05	0.07	8.06	11.46	0.83	0.69	0.10	16.21
Mean Propulsive Power (W)	2396.88	380.98	2371.43	380.31	25.45	157.50	111.37	158.45	4.67	6.65	0.96	0.92	224.08	9.40
Peak Propulsive Power (W)	3952.83	555.76	3940.65	538.32	12.18	210.99	149.19	212.26	3.78	5.38	0.96	0.93	300.17	7.61
Net Impulse Ratio (AU)	2.19	0.37	2.10	0.30	0.09	0.22	0.15	0.22	7.11	10.12	0.87	0.74	0.31	14.31
Mean Propulsive Force (N)	1719.43	249.92	1683.01	244.53	36.42	91.78	64.90	92.33	3.81	5.43	0.96	0.92	130.57	7.68
Peak Propulsive Force (N)	2311.24	506.60	2235.11	512.47	76.13	199.04	140.74	200.23	6.19	8.81	0.96	0.91	283.17	12.46
Countermovement Depth (m)	0.21	0.06	0.23	0.06	0.01	0.03	0.02	0.03	8.70	12.38	0.92	0.82	0.04	17.51
Braking RFD (N/s)	16305.74	10847.69	15009.82	10883.36	1295.92	5245.31	3708.99	5276.80	23.69	33.70	0.94	0.88	7462.52	47.66
Mean Braking Power (W)	1056.61	245.03	1092.74	223.33	36.13	136.96	96.85	137.79	9.01	12.82	0.90	0.82	194.86	18.13
Peak Braking Power (W)	1487.61	436.60	1531.27	367.11	43.67	247.67	175.13	249.15	11.60	16.51	0.90	0.81	352.36	23.34
Net Braking Impulse (N.s)	84.73	16.37	88.45	14.46	3.72	8.10	5.73	8.15	6.62	9.41	0.91	0.82	11.53	13.31
Mean Braking Force (N)	1532.02	283.09	1533.05	263.70	1.03	118.32	83.67	119.03	5.46	7.77	0.95	0.91	168.34	10.98
Peak Braking Force (N)	2194.62	501.25	2144.90	510.13	49.72	216.53	153.11	217.83	7.06	10.04	0.95	0.91	308.05	14.20
Body Weight (N)	705.68	69.16	707.03	67.41	1.35	6.40	4.53	6.44	0.64	0.91	1.00	1.00	9.11	1.29

Key: SD, standard deviation; SEM, standard error of measurement; CV, coefficient of variation; ICC, intraclass correlation coefficient; MDC, minimal detectable change; mRSI, modified reactive strength index; FT:CT, flight time contraction time ratio; RFD, rate of force development; AU, arbitrary unit; m, metres; s, seconds; Kg, kilograms; N, Newtons; W, watts; dark green cell shading, excellent reliability; bright green cell shading, good reliability; orange cell shading, moderate reliability; red cell shading, poor reliability.

Table 7.9. Descriptive and Reliability Statistics of Countermovement Rebound Jump Test Metrics (Rebound Jump Portion).

RJ Portion Metrics	Session 1		Session 2		Mean Difference	SD	SEM	SEM +95	CV	CV +95	ICC	ICC -95	MDC	MDC %
	Mean	SD	Mean	SD										
RSI (AU)	1.50	0.45	1.41	0.44	0.09	0.29	0.20	0.29	14.04	19.98	0.87	0.76	0.41	28.25
FT:CT (AU)	2.33	0.55	2.19	0.59	0.15	0.35	0.25	0.35	10.95	15.58	0.88	0.77	0.50	22.03
Jump Height (m)	0.33	0.05	0.33	0.05	0.00	0.03	0.02	0.03	7.22	10.27	0.88	0.77	0.05	14.52
Flight Time (s)	0.52	0.04	0.52	0.04	0.00	0.03	0.02	0.03	3.43	4.88	0.88	0.78	0.04	6.90
Jump Momentum (Kg*m/s)	182.73	18.99	183.78	19.36	1.04	9.12	6.45	9.18	3.52	5.01	0.94	0.89	12.98	7.08
Takeoff Velocity (m/s)	2.55	0.20	2.56	0.20	0.01	0.13	0.09	0.13	3.64	5.18	0.88	0.77	0.19	7.33
Ground Contact Time (s)	0.22	0.06	0.24	0.08	0.02	0.05	0.03	0.05	12.99	18.48	0.87	0.71	0.06	28.43
Stiffness (N/m)	44735.57	55148.24	38184.85	45531.00	6550.71	17647.50	12478.67	17753.46	29.77	42.82	0.94	0.88	25107.18	60.56
Mean Propulsive Power (W)	3247.33	618.56	3121.95	632.18	125.38	394.01	278.61	396.38	8.75	12.45	0.88	0.78	560.56	17.60
Peak Propulsive Power (W)	5309.16	1083.98	5089.25	1078.42	219.92	653.18	461.87	657.10	8.88	12.64	0.89	0.80	929.28	17.87
Net Impulse Ratio (AU)	1.00	0.06	0.99	0.05	0.01	0.05	0.03	0.05	3.28	4.67	0.80	0.63	0.07	6.61
Mean Propulsive Force (N)	2247.84	373.13	2151.76	385.87	96.08	212.67	150.38	213.95	6.84	9.73	0.90	0.79	302.57	13.75
Peak Propulsive Force (N)	3743.44	949.01	3577.79	1039.99	165.65	481.61	340.55	484.50	9.30	13.24	0.93	0.87	685.18	18.72
Braking Depth (m)	0.13	0.06	0.14	0.06	0.02	0.04	0.03	0.04	20.21	28.76	0.88	0.74	0.06	40.67
Mean Braking Power (W)	3499.77	719.22	3422.03	746.10	77.74	434.84	307.48	437.45	8.88	12.64	0.90	0.82	618.64	17.88
Peak Braking Power (W)	6797.29	1308.46	6752.11	1258.29	45.18	829.31	586.41	834.29	8.66	12.31	0.89	0.79	1179.87	17.42
Net Braking Impulse (N.s)	181.97	19.85	185.02	19.32	3.04	8.02	5.67	8.06	3.09	4.39	0.95	0.90	11.40	6.21
Mean Braking Force (N)	2478.37	481.46	2390.72	502.97	87.65	271.68	192.11	273.31	7.89	11.23	0.91	0.83	386.52	15.88
Peak Braking Force (N)	4166.77	955.37	4011.50	1073.03	155.27	523.44	370.13	526.58	9.05	12.88	0.93	0.86	744.70	18.21

Key: SD, standard deviation; SEM, standard error of measurement; CV, coefficient of variation; ICC, intraclass correlation coefficient; MDC, minimal detectable change; RSI, reactive strength index; FT:CT, flight time contraction time ratio; AU, arbitrary unit; m, metres; s, seconds; Kg, kilograms; N, Newtons; W, watts; dark green cell shading, excellent reliability; bright green cell shading, good reliability; orange cell shading, moderate reliability; red cell shading, poor reliability.

7.5 DISCUSSION

Because of the absence of peer-reviewed test-retest reliability studies involving CMJ force-time metrics obtained with professional soccer players, the aim of “study a” was to determine the test-retest reliability of a range of CMJ outcome, kinetic, and strategy metrics in professional soccer players during the pre-season period. Outcome and kinetic measures were most reliable, followed by strategy and ratio metrics. It was hypothesised that reliability would be better for propulsive- over countermovement-phase (i.e., unweighting and braking phase) force-time metrics. This hypothesis is accepted based on the results of this study, where only propulsive phase kinetic (and not braking phase) metrics were reliable.

The aim of “study b” was to determine the test-retest reliability of a range of CMJ, CMRJ, DJ, and IMTP ratio, outcome, kinetic, and strategy metrics in youth soccer players during the pre-season period. Due to the observation in previous research that CMJ test-retest reliability improved with developmental age (maturation) [292], it was hypothesised that reliability would be better for professional soccer players (reported in “study a”) compared to youth soccer players (reported in “study b”) in the pre-season period. This hypothesis was confirmed as despite “study b” including a similar number of CMJ metrics (N = 27; Table 7.2) to “study a” (N = 28; Table 7.1), acceptable absolute and relative reliability was demonstrated in less than half the number of CMJ metrics in “study b” (N = 5) than “study a" (N = 13). However, this seems to be an issue with the homogeneity of physical capacity in youth athletes which has negatively affected the ranking of scores (i.e., relative reliability) [206], as the variability (i.e., absolute reliability) between sessions was similar, particularly for outcome metrics.

The aim of “study c” was to determine the test-retest reliability of a range of CMJ and CMRJ ratio, outcome, kinetic, and strategy metrics in youth soccer players during the in-season period. To the author’s knowledge, this study is the first to report the test-retest reliability of the CMRJ test in youth soccer players in the in-season period. The authors accept the original hypotheses because the reliability of the CMJ outcome measures were acceptable for full-time youth soccer players similar to determinations made in previous research [292], the reliability of outcome measures during the CMJ portion of the CMRJ test were acceptable confirming that the test can avoid discrepancies in fall height previously reported in the DJ test (which was not the case for youth during pre-season in “study b”), and reliability was better for propulsive-over countermovement-phase force-time metrics in the CMJ test, as seen previously [65, 68-70, 293].

7.5.1 Countermovement Jump

7.5.1.1 Weighing

The accurate collection and calculation of bodyweight during VJ tests is essential for the calculation of specific measures from force-time data relating to force, impulse, and acceleration production. Data analysis software (e.g., proprietary software, Microsoft Excel, MatLab, R, etc.) is used to produce force-time curves and, in VJ tests, forward dynamics is applied to calculate a multitude of performance metrics relating to acceleration, velocity, and displacement [25]. Thus, a lack of reliability through high variability in body weight will falsely represent an athlete's body weight and affect the calculation of specific measures related to the outcome (i.e., JH) of a VJ test, such as relative force and impulse production, propulsive acceleration, jump momentum, and TOV [15, 177, 184, 288]. Bodyweight demonstrated excellent absolute and relative reliability during the CMJ test in professional soccer players during the pre-season period (i.e., in "study a"), in youth soccer players during the pre-season period (i.e., in "study b"), and in youth soccer players during the in-season period (i.e., in "study c"). These results provide confidence that body weight had no negative influence on the reliability seen in other metrics within this chapter. Additionally, professional soccer players in "study a" (Table 7.1) demonstrated similar reliability to youth soccer players in "study b" (Table 7.2) in body weight in the pre-season period with an almost exact CV (1.13% vs 1.24%) and ICC (1.00 vs 0.99). Thus, these results suggest the reliability of the measurement of body weight during the CMJ test is not affected by age or competitive level (i.e., professional vs youth) and any subsequent reliability differences in CMJ ratio, outcome, strategy, or kinetic metrics between "study a" and "study b" is not due to differences in the reliability of body weight.

In VJs, TOV is determined by relative net propulsive impulse production, thus, an athlete with a greater body mass will be required to produce a greater net propulsive impulse to produce the same TOV and JH as a lighter athlete [15, 177]. The results of a previous study identified that mass-relative force-time metrics explain 85.08% of variance of CMJ performance, with relative mean and peak concentric power the most related to the outcome [32]. Changes in body weight are likely from pre- to post-match in soccer players due to the loss of fluid through perspiration, which might induce a change in specific kinetic and outcome measures, which could be incorrectly interpreted as a change in NMF if body weight is not monitored correctly. Thus, in practice, monitoring changes in body weight independently would provide information regarding whether changes in key kinetic, strategy, outcome, and ratio metrics were due to independent changes in NMF or bodyweight, or a combination of both [15, 184, 288]. In "study a", the mean difference in body weight between testing sessions was 2.19 N (0.22 kg), and the minimal change required in body weight to deem a change as meaningful (i.e., the MDC) was 12.90 N (1.32 kg). In "study b", the mean difference in body weight between testing sessions was 1.78 ± 7.81 N, and the minimal change required in body weight to deem a change as meaningful (i.e., the MDC) was 12.55 N (1.28 kg; 1.76%). In "study c", the minimal change required in body weight to deem a change as meaningful (i.e., the MDC) was 1.37%, or 9.69 N (0.98 kg). Future studies can utilise these results to interpret changes in body weight from the CMJ test in soccer players by deciding whether an observed change exceeds the MDCs stated here [15, 184, 288]. However, calculating the reliability and MDCs of body mass within every independent population being assessed is still advised [15, 184, 288].

7.5.1.2 Outcome Metrics

Outcome metrics are the most frequently considered measures in scientific literature and the practical setting [23, 310], most likely due to their direct association with the performance of a variety of sports tasks and tests of NMF (e.g., sprint and COD speed) in athletes [311, 312]. To the author's knowledge, only one previous study has assessed the absolute and relative reliability of CMJ force-time metrics in youth soccer players [292], and the absolute and relative reliability of CMJ outcome metrics such as FT, jump momentum, and TOV in youth soccer players has not been reported in literature [292]. Of the outcome metrics assessed, authors of previous research have reported acceptable reliability for only JH in youth soccer players, however, 95% CIs were not reported [292]. Four CMJ outcome metrics were assessed within this chapter, which included TOV, jump momentum, FT, and JH. In "study a", outcome metrics were typically more reliable than strategy and kinetic metrics, which mirrors the results of a recent test-retest reliability study by Anicic et al. [293] with a sample of adult male and female physically active participants. Additionally, all CMJ outcome metrics demonstrated acceptable absolute and relative reliability in professional soccer players in the pre-season period (i.e., in "study a") and in youth soccer players in the in-season period (i.e., in "study c"), which is in agreement with the findings of previous studies assessing the test-retest reliability of CMJ metrics in adult male [206, 313] and female [206, 313, 314] participants which demonstrated acceptable absolute and relative reliability for metrics such as JH [206, 313, 314], FT [206], and jump momentum [314].

The results of "study b" are the first to illustrate that FT, jump momentum, and TOV demonstrate acceptable absolute reliability, but only jump momentum demonstrates acceptable relative reliability, in youth soccer players in the pre-season period (Table 7.2). The findings of "study b" (Table 7.2) followed a similar pattern to those of "study a" (Table 7.1), where jump momentum, FT, and TOV displayed better absolute reliability than JH in professional soccer players but instead indicated that (in addition to JH) FT and TOV were unacceptable at maintaining rank within a squad between-sessions in youth soccer players. A potential explanation for this could be due to the homogeneity in physical capacity typically seen within youth age groups in soccer [206]. Homogeneity can negatively affect the precision of relative reliability scores due to the potential of a reduced spread of scores across the group [206]. Therefore, similar scores in a metric across a squad of youth soccer players would result in more potential for a change in rank of scores between sessions. This raises a potential problem for the establishment of relative reliability of metrics in youth soccer players, where if the ICC is considered a valuable part of the reliability determination, outcome metrics would mostly be deemed as unacceptable for monitoring changes in NMF in the pre-season period. In every study within this chapter, jump momentum demonstrated the best reliability of all CMJ outcome measures, followed by FT, TOV, and JH. This is understandable when you consider the biomechanical underpinnings of VJ tests [15, 177]. Jump momentum is the change in propulsive velocity of the system multiplied by body mass [15, 177]. In VJs, velocity is zero at the beginning of the propulsion phase, and so jump momentum equals TOV multiplied by body mass [15, 177]. Consequently, it is not surprising that when TOV is multiplied by body weight (which displayed the best reliability of all metrics in every study) the reliability of the resultant jump momentum metric would be acceptable.

Based on the impulse-momentum theorem, jump momentum is equal to net propulsive impulse (propulsive mean force x propulsive phase time), so the reliability of each measure is assumed to be the same [15, 177]. Despite momentum being useful in certain sports (e.g., rugby), soccer players are required to produce the greatest net propulsive impulse possible to act *against* their body weight to accelerate it rapidly. Thus, in soccer players, it might be more appropriate to monitor propulsive impulse *relative* to system mass, which equals TOV [25, 88]. Where jump momentum (TOV x bodyweight) is equal net propulsive impulse, TOV alone is equal to propulsive net impulse relative to body weight [15, 177]. Despite demonstrating slightly worse (yet still good to excellent) absolute reliability than jump momentum throughout this chapter, TOV might offer a more theoretically meaningful option for determining acute changes in NMF in soccer players as it also relates to sprinting velocity [315], which is an important component of success in soccer (e.g., in goal scoring situations). However, given TOV is a mass relative measure, consideration must be also given to monitoring changes in body weight independently to determine if a change is due to changes in net propulsive impulse production (i.e., jump momentum) or body weight, or a combination of both [15, 184, 288]. As jump momentum in the monitoring process would also give an indication of changes in net propulsive impulse production, including a combination of CMJ derived TOV, jump momentum, and body weight might be most appropriate for monitoring acute changes in NMF.

Of all outcome metrics, JH is the most common CMJ metric reported in literature [23]. It is a measure of interest as it is intuitive to athletes and coaches and associates with specific KPIs in sports (e.g., linear and COD speed) [115]. Based on a deterministic model of VJ performance by Hay & Reid [177], TOV directly determines JH, where JH was calculated as TOV squared / (2 × g) in this chapter [230]. Thus, one might assume that a reliable TOV would produce a similarly reliable JH [15, 177]. However, the calculation of JH resulted in the absolute reliability of JH being twice that of TOV in "study c" (6.05% vs 3.02%), specifically [72]. To the author's knowledge, only one previous study has reported acceptable absolute reliability (i.e., CV < 10%) for JH in youth soccer players [292]. Chronologically, these athletes were part of the male "U17" age group, which corresponded to a post-PHV maturational grouping [292], similar to the subjects of "study b" and "study c". Ruf et al. [292] reported a CV% of 6.6% for CMJ JH, but did not consider +95% CIs in their analysis, which amplified the CV% to 10.58% for JH in "study b", specifically, which was deemed unacceptable. Similarly, JH demonstrated acceptable relative reliability based on the ICC in "study b", but not based on the -95% CI (Table 7.2). Such findings are not uncommon within literature, where JH has been considered as not sensitive enough to detect change (i.e., did not demonstrate meaningful change) after intense physical activity in other populations [42, 115]. Therefore, contrary to the conclusions of Ruf et al. [292], the results of "study b" suggest that JH does not demonstrate acceptable reliability in youth soccer players in the pre-season period, which highlights the need for future studies assessing the test-retest reliability of force plate derived CMJ force-time metrics to consider reporting the 95% CIs of the CV and ICC. Despite this, JH demonstrated good to excellent reliability in professional soccer players in the pre-season period (i.e., in "study a") and in youth soccer players in the in-season period (i.e., in "study c") based on 95% CIs of the CV and ICC.

Biomechanically, TOV provides the same theoretical rationale without the worsened reliability due to the calculation of JH [15, 28, 177]. Thus, if JH is a measure of interest (e.g., due to its associations with specific KPIs in sports [115]), utilising TOV instead of JH might be a better alternative because JH is the direct result of an athlete's TOV in VJ tests conducted on force plates (calculated as TOV squared / (2 × g) [15, 28, 177]). Additionally, despite demonstrating acceptable reliability in "study a" and "study c", changes in take-off and touchdown posture, and artificially extending the flight phase (e.g., via tucking the legs) can cause an erroneous measure of FT [59]. Additionally, the thresholds used for identifying the instants of take-off and touchdown [15, 177] also make the standardisation of data collection and analysis procedure vital to the metric's reliability. Generally, it is important to emphasise the administration of correct and consistent VJ technique, calculations of body weight, and data analysis procedures (e.g., phase identification threshold) during VJ tasks on force plates if utilising FT and other outcome metrics to monitor acute changes in NMF.

In addition to the reliability of a metric, the size of the required change in a metric's value for it to be considered "meaningful" must also be considered. The MDC for reliable metrics such as jump momentum, FT, TOV, and JH equalled 3.21% (7.10 kg*m/s), 3.27% (0.02 s), 3.37% (0.09 m/s), 6.82% (0.03 m), respectively, in professional soccer players in the pre-season period (i.e., in "study a"). Based on the results of "study b", only jump momentum can be considered as a reliable CMJ outcome metric for youth soccer players in the pre-season period, where the MDC for jump momentum in youth soccer players in the pre-season period in "study b" (13.62 kg*m/s; Table 7.2) was almost double that seen in professional soccer players in the pre-season period in "study a" (7.10 kg*m/s; Table 7.1). As such, it can be suggested that the reliability of CMJ outcome measures is better in professional soccer players as opposed to youth soccer players in the pre-season period, as was originally hypothesised. When monitoring changes in NMF in youth soccer players using the CMJ test in the in-season period, TOV, jump momentum, FT, and JH can all be considered reliable outcome metrics. The MDCs that can be applied practically for these measures equal 4.28% (0.11 m/s), 4.43% (8.29 kg*m/s), 4.75% (0.03 s), and 8.55% (0.03 m), respectively. Practitioners must determine if a change of this amount in the proposed metrics is acceptable within the specific soccer populations they work with. The most appropriate outcome metric to monitor for soccer players might be TOV (or JH), but only if concurrently accounting for changes in jump momentum and body weight.

7.5.1.3 Strategy Metrics

Despite receiving less attention in scientific literature when compared to outcome and kinetic metrics [15, 23], strategy metrics provide an opportunity to quantitatively portray the jump strategy used to achieve a given VJ outcome [184, 293]. Monitoring CMJ outcome metrics alone will result in a practitioner missing key information about the strategy adopted to achieve the outcome. Because a change in strategy is a result of altered force-time characteristics, this oversight might cause issues in the determination of changes in NMF [184]. For example, a CMJ trial performed with a greater countermovement depth typically corresponds with a greater time to take-off and thus net propulsive impulse, if propulsive force production is not substantially reduced [184]. A greater generation of net propulsive impulse relative to body weight would increase TOV and thus JH [177, 184]. Therefore, if CMJ strategy is not monitored, an alteration in strategy might alter the outcome metrics of a trial which may be incorrectly perceived as a change in NMF.

The six CMJ strategy metrics that were assessed in "study a" demonstrated worse reliability than all outcome measures, and most kinetic measures, with no CMJ strategy metrics demonstrating acceptable absolute or relative reliability in professional soccer players in the pre-season period. Similarly, the results of "study b" also demonstrated unacceptable absolute and relative reliability for all CMJ strategy (N = 5) metrics assessed in youth soccer players in the pre-season period (Table 7.2). The limited reliability demonstrated in strategy measures in both youth and professional soccer players in the pre-season period is concerning given that these metrics are typically proposed to provide an insight into the jump strategy performed to achieve a given VJ outcome [184, 293]. Five CMJ strategy metrics were also assessed in "study c", which included unweighting phase time, braking phase time, countermovement depth, propulsive phase time, and time to take-off, where only countermovement depth and propulsive phase time demonstrated acceptable absolute and relative reliability in youth soccer players in the in-season period. Thus, it appears that CMJ strategy metrics often demonstrate too large variability to be considered for the monitoring of acute change in NMF in soccer players, despite a necessity to monitor the influence of strategy on the outcome of the task.

The findings presented in this chapter agree with previous reliability research utilising male and female participants with various sporting backgrounds, where poor reliability in "kinematic metrics" such as unweighting and braking phase time has been demonstrated [206, 293]. Previous discussions have considered the potential that a greater number of computational steps required to calculate strategy metrics may negatively affect the reliability of these measures, and less so in metrics directly calculated from the force–time curve (i.e., outcome and kinetic metrics) [293]. Alternatively, this variability in CMJ strategy could be due to a lack of familiarity with the task and training status, as testing in "study a" and "study b" was conducted on the first and eighth day of the EFL pre-season period, and testing in "study c" was conducted on the first and eighth day of an in-season formative evaluation period with no prior contact with the sample. Thus, one could assume that this variability in CMJ strategy metrics could be partly due to the sample's lack of familiarity with the testing procedures within this chapter. It would be useful for future research to investigate whether the reliability of CMJ strategy metrics improves using a repeated measures design over a period of consecutive weeks (e.g., 4 to 6 weeks) to increase athletes' familiarity with testing procedures, or from pre- to in-season as athletes increase their fitness and familiarity with testing.

7.5.1.4 Ratio Metrics

Ratio metrics are an extension of outcome measures which provide information of the relationship between two separate components of NMF [293]. Primarily, they have been popularised as an indicator of SSC capacity which consider both the outcome achieved and strategy performed to achieve this within a single measurement [316]. This is typically done by dividing one measure (e.g., JH) by another (e.g., time to take-off) to create a ratio metric (e.g., mRSI) which has an arbitrary unit of measurement [293]. Of the three CMJ ratio metrics assessed within this chapter, which included net impulse ratio, FT:CT, and mRSI, none demonstrated acceptable absolute or relative reliability in professional soccer players in the pre-season period (i.e., in "study a"), in youth soccer players in the pre-season period (i.e., in "study b"), or in youth soccer players in the in-season period (i.e., in "study c"). Concerningly, this means that "study b" has illustrated that no CMJ outcome measures (other than jump momentum), strategy, or ratio measures demonstrated acceptable absolute and relative reliability, and thus an acceptable ability to monitor changes in NMF, in youth soccer players, which is in line with previous reports in youth soccer players [292]. However, these results are contrary to previous studies results which reported acceptable absolute reliability in CMJ-derived mRSI in adult male and female recreationally active participants [293] and female volleyball athletes [60]. The primary reason for this discrepancy might be the interpretation of the results, where these studies discussed reliability based on the CV% without considering the 95% CIs [60, 293]. For comparison, the results of "study a" also demonstrated acceptable absolute reliability in CMJ-derived mRSI based only on the CV%, and the results of the "study c" also demonstrated acceptable reliability in CMJ-derived net impulse ratio and FT:CT based only on the CV% and ICC. Therefore, these researchers might not have come to this conclusion had they considered the 95% CIs of measures in their interpretations [60, 293].

The limited reliability demonstrated in ratio metrics in both youth and professional soccer players is concerning given that insight into more than just the outcome via relating it to the jump strategy performed to achieve a given VJ outcome is valued to coaches [184, 293].

Similarly acceptable within-session reliability has been reported for CMJ-derived FT:CT and mRSI in previous research [59], concluding that either metric can be utilised reliably for physical profiling, but the use of both metrics is not necessary and they should not be used interchangeably. However, an issue with the test-retest reliability of FT:CT and mRSI within this chapter is the poor test-retest reliability demonstrated in strategy metrics. In this chapter, FT:CT was calculated as FT divided by time to take-off, and mRSI was calculated as JH divided by time to take-off, as per the data analysis methodologies of the force plate system. As discussed, although outcome measures such as FT and JH displayed acceptable reliability in "study a" and "study c", when combined in an equation with strategy metrics (i.e., time to take-off) the reliability of the resultant FT:CT and mRSI worsened. Similarly, net impulse ratio is comprised of net propulsive divided by net braking impulse, and as the latter displayed unacceptable absolute reliability in "study a" and "study b" (but not "study c"), the absolute reliability of the resultant net impulse ratio was also unacceptable. For this reason, ratio metrics were less reliable than all outcome metrics, most kinetic metrics, and some strategy metrics in all studies. Thus, despite the growing popularity of ratio metrics [26, 165, 266], these results suggest that monitoring components separately might be a more appropriate approach.

7.5.1.5 Kinetic Metrics

Where strategy and ratio metrics have presented limited reliability, kinetic metrics might present an alternative opportunity to provide an in-depth insight into the mechanisms which determine CMJ execution [293, 317], exclusive of the variability seen in CMJ strategy metrics in this chapter. Previous research has reported that metrics derived from the downward (i.e., unweighting and braking) phase of the force–time curve tend to have greater variability than the metrics derived from the upward (i.e., propulsive) phase of CMJs [293, 313]. In "study a", eight out of the 14 included CMJ kinetic metrics demonstrated acceptable absolute and relative reliability in professional soccer players in the pre-season period. Interestingly, reliable measures mostly occurred within the propulsive phase of the CMJ test, which were peak propulsion velocity, mean propulsive velocity, peak propulsive power, mean propulsive force, mean propulsive power, and peak propulsive force. In "study a", peak braking force was the only reliable kinetic measure of the braking phase. Peak propulsive power, mean propulsive force, and mean propulsive power also demonstrated acceptable absolute and relative reliability in "study b", illustrating that these metrics can be used to monitor acute changes in NMF from the post-PHV to professional levels in soccer players in the pre-season period. Interestingly, these metrics also occurred during the propulsive phase where none of the eight included braking phase metrics in "study b" demonstrated acceptable reliability (Table 7.1). These results are also corroborated in "study c", where only net braking impulse demonstrated acceptable absolute and relative reliability, and the remaining six kinetic metrics which demonstrated excellent to good absolute and relative reliability occurred within the propulsive phase of the CMJ test. These metrics included peak velocity, mean propulsive velocity, peak propulsive force, mean propulsive force, peak propulsive power, and mean propulsive power. These findings confirm the original hypothesis that reliability would be better for propulsive phase over braking phase CMJ metrics, which was based on the conclusions of previous research [293, 313].

The results presented within this chapter are both valuable and understandable because the force-time characteristics of the propulsive phase directly influence TOV, and thus JH [15, 177], which would explain the acceptable reliability demonstrated in outcome metrics in these studies. Contrary to these findings, research outside of soccer has reported CV values of less than 10% in some braking phase metrics (specifically peak and mean braking force), and suggested that these might be reliable and sensitive enough to determine acute changes in NMF [293, 313]. "Concentric impulse" (i.e., propulsive impulse) was one of only three measures including JH and "concentric velocity" reported as demonstrating acceptable absolute reliability in the study by Ruf et al. [292] in youth soccer players. However, as critiqued earlier, the researchers formulated these decisions based on reliability values without considering the 95% CI, which would have amplified reliability. Additionally, "concentric" phase metrics is incorrect terminology when assessing CMJ performance using force plates [115]. The term "concentric" suggests that the muscles are actively shortening, which is not possible to determine from force plate analysis [115]. Instead, metrics should be categorised based on distinct phases prior to take-off termed the "unweighting", "braking", and "propulsion" phases, which can be determined using methods proposed in literature [25].

Based on the current results demonstrating greater reliability in propulsive phase measures over braking phase measures, practitioners should consider propulsive phase measures over braking phase measures for the monitoring of NMF in soccer players. Specifically, peak velocity, mean propulsive velocity, peak propulsive power, mean propulsive force, mean propulsive power, and peak propulsive force could be used alongside outcome measures in professional soccer players in the pre-season period to provide an illustration of force-time characteristics of the CMJ test, and thus how the outcome was achieved, as opposed to specific strategy measures which demonstrated poor reliability. Regarding the practical application of these metrics, an

MDC equal to 3.16% (0.09 m/s), 5.11% (0.09 m/s), 6.72% (287.20 W), 8.77% (148.53 N), 10.33% (262.74 W), 13.80% (293.42 N), respectively, can be considered reliable values. The MDC calculated for reliable metrics such as peak propulsive power, mean propulsive force, and mean propulsive power in "study b" that can be applied for youth soccer players in the pre-season period equalled 10.69% (434.21 W), 11.28% (197.61 N), and 12.95% (318.41 W), respectively (Table 7.2).

Peak velocity, mean propulsive velocity, mean propulsive force, peak propulsive power, mean propulsive power, and peak propulsive force could be considered alongside outcome measures in youth soccer players in the in-season period to provide an illustration of the force-time characteristics of CMJ trials and thus how the outcome was achieved, as opposed to strategy measures which demonstrated limited reliability. Regarding the practical application of these metrics for monitoring acute changes in NMF, an MDC equal to 4.11% (0.11 m/s), 4.93% (0.08 m/s), 7.43% (121.33 N), 8.02% (313.78 W), 9.38% (220.45 W), and 12.76% (268.17 N), respectively, can be considered as reliable. However, practitioners are encouraged to determine their own reliability of values of interest within the specific sports, age groups, and environments in which they work. Additionally, it must be stated that peak measures are affected by a change in strategy, where a "stiffer" strategy (i.e., less countermovement depth and time to take-off) typically elicits greater peak forces but less propulsive phase time and resultantly less net propulsive impulse [184]. Given that small increases in braking phase time, propulsive phase time, and time to take-off have been seen at 72 hours post- a 3-stage Yo-Yo fatiguing protocol [65], monitoring changes in peak values might not be most suitable.

7.5.2 Countermovement Rebound Jump

To the author's knowledge, "study b" and "study c" are the first studies to report the test-retest reliability of the CMRJ test in youth soccer players in the pre-season and in-season periods, respectively.

7.5.2.1 CMJ Portion

The CMRJ test is proposed as an assessment of fast SSC capacity. Thus, the performance of the CMJ portion is not of interest regarding the assessment of NMF, where its sole purpose is to achieve a JH which provides a fall height for the RJ portion. This replaces the equivalent fall height from a box as seen in the DJ test, which has demonstrated variability in previous research [170]. For example, Geraldo et al. [170] reported a fall height of 13.7 ± 1.6 cm from a 20 cm effective box height and 29.4 ± 2.6 cm from a 40 cm effective box height. Thus, the utility of the CMRJ test relies upon the reliability of the preceding CMJ (i.e., fall height of the RJ portion), and how this compares to the unacceptable variability in fall height in DJs reported in previous research [21, 170, 171]. Because the CMJ portion replaces an equivalent drop from a box, outcome metrics are of primary interest in the CMJ portion, as a consistent fall height in the RJ portion is essential for the reliable performance of the RJ phase (i.e., consistent touch-down velocity). Interestingly, the absolute and relative reliability of metrics during the CMJ portion of the CMRJ test mimic the reliability of the independent CMJ test in "study b", with metrics such as body weight, peak propulsive power, jump momentum, and mean propulsive force demonstrating acceptable absolute and relative reliability. This is positive as it indicates that the CMJ portion of the CMRJ test is as reliable as the independent CMJ test between-sessions. Xu et al. [173] also reported that the CMJ test and CMJ portion of the CMRJ test have demonstrated similar absolute reliability in metrics such as JH (CV = 4.19% and 4.86%, respectively) and CM depth (CV = 7.20% and 7.01%, respectively).

In "study b", an average 2 cm reduction (17.48%) in CMJ portion JH from week 1 to 2 resulted in unacceptable absolute and relative reliability in JH. Theoretically, this hinders the rationale for utilising the CMRJ test as an alternative to the more traditional DJ test which also demonstrates unacceptable reliability in fall height research [171]. However, as stated above, the absolute reliability in JH in the CMJ portion (12.3%; Table 7.3) was similar to that of the CMJ test (10.6%; Table 7.2) in "study b", like what was reported by Xu et al. [173]. Additionally, this is less than previously reported discrepancies between DJ box height and fall height reported in previous research by Geraldo [170] performed from 20 cm (-31.5%) and 40 cm (-33.5%) box heights. Therefore, although this is not ideal for the performance of the RJ portion, it is seemingly not unusual compared to the variability of the independent CMJ test performed by this cohort, and still presents better variability than that seen between box height and fall height in the DJ test. In addition, JH TOV, and jump momentum demonstrated acceptable absolute and relative reliability based on the 95% CIs in "study c", which confirms the original hypothesis that the reliability of outcome metrics during the CMJ portion of the CMRJ test would be acceptable in youth soccer players in the in-season period. Taking all of this into account, it seems rational to consider that the lack of reliability in CMJ portion JH in "study b" is a limitation of the specific cohort, and not a limitation of the test itself.

The CMRJ may be considered as a reliable alternative to the DJ test for the assessment of fast SSC capacity in youth soccer players in the in-season period, as it overcame the issues of variability in fall height previously demonstrated in the DJ test [170, 171], which was not the case for youth in pre-season. Body weight also demonstrated excellent reliability; therefore, the reliability of RJ metrics was not affected by differences in bodyweight or fall height in youth soccer player in the in-season period. Technique-intensive tests generally exhibit greater variability in results and require more pre-test practice to produce consistency, and therefore, greater reliability might be seen from an athlete with more experience with a task [36]. Therefore, in the pre-season period, youth soccer players may benefit from more development of physical capacity and familiarity to force plate tests to produce acceptable reliability. As has been recommended in previous research [187, 189], the prescription of additional familiarisation to these tests may have improved the reliability of these metrics in this cohort. Future research should assess whether the reliability of CMJ and CMJ portion JH in youth soccer players improves over time with more familiarity with the test.

7.5.2.2 RJ Portion

The RJ portion of the CMRJ test seemingly provides unacceptable reliability and thus an inadequate ability to monitor changes in NMF in youth soccer players, in the pre-season period (Table 7.4). This is due to only net braking impulse demonstrating acceptable absolute and relative reliability, based on the 95% CIs, in “study b”. One could assume that this is due to the unacceptable reliability demonstrated in JH in the CMJ portion, however, net braking impulse was seemingly unaffected by this, and the absolute and relative reliability results illustrate different patterns when considered independently. As would be expected following a reliable CMJ portion JH in “study c”, which generates an equivalently reliable fall height and thus touch-down velocity, net braking impulse also demonstrated acceptable absolute and relative reliability based on the 95% CIs in youth soccer players in the in-season period. Therefore, monitoring net braking impulse in the RJ portion might be used an alternative to monitoring outcome measures in the CMJ portion to determine fall height consistency, if required. In “study b”, many of the RJ portion metrics such as jump momentum, FT, mean propulsive force, mean propulsive power, and peak propulsive power demonstrated acceptable absolute reliability, however, the RJ portion metrics seem to have a poorer ability to rank athletes within a squad where only peak braking power and net braking impulse demonstrated acceptable relative reliability. As considered previously, this could be an issue with the homogeneity of physical capacity in youth athletes which affects the ranking of scores [206]. This again raises the question around the utility of relative reliability measures in determining whether a metric is suitable for monitoring acute changes in NMF in youth soccer players, because its inclusion in “study b” has rendered many of the CMJ test and CMRJ test metrics as unfit for this purpose.

The primary purpose of evaluating the RJ portion is to assess fast SSC capacity, which is typically done via metrics associated with “reactivity” or “reactive strength” [229]. Concerningly, such metrics demonstrated poor absolute reliability in this chapter, such as FT:CT (CV = 15.58%), RSI (CV = 19.98%), and stiffness (CV = 42.82%) in “study c”. This was primarily caused by poor absolute reliability demonstrated in strategy metrics, such as GCT (CV = 18.48% in “study c”) and braking depth (CV = 28.76% in “study c”), whilst outcome metrics such as FT, jump momentum, and TOV demonstrated excellent to good absolute reliability. Moreover, besides net braking impulse, and the outcome metrics listed, only mean propulsive force demonstrated acceptable absolute and relative reliability for the RJ portion in youth soccer players in the in-season period. These findings may present issues for the application of the CMRJ test for the monitoring of acute changes in NMF in youth soccer players, as primary metrics of interest (e.g., FT:CT, RSI, and stiffness) demonstrated unacceptable absolute reliability and thus are deemed unfit for this purpose. However, good relative reliability was still demonstrated for FT:CT (0.77), RSI (0.76), and stiffness (0.88) in “study c” which might present an opportunity to still assess these measures in formative evaluation periods performed 3 to 4 times per season and used to rank players physical capacity within a squad (i.e., for benchmarking). Moreover, it should be stated that ratio measures are utilised to provide additional context besides outcome metrics (i.e., regarding the way the outcome was performed), where the outcome metric is the more primary KPI of interest and typically demonstrates better between-session reliability, as demonstrated in this study.

When considering ratio metrics (e.g., RSI), it must be stated that the component parts of a ratio (e.g., JH and GCT) should also be monitored to provide context for changes in the ratio measure. Overall, FT, jump momentum, TOV, and mean propulsive force can be considered reliable RJ portion metrics for monitoring acute changes in NMF in youth soccer players in the in-season period. Monitoring these metrics will provide an understanding of the outcome (e.g., TOV) and its components which are jump momentum (equivalent to net propulsive impulse), mean propulsive force, and body weight (collected in the CMJ portion). However, net propulsive impulse can be manipulated via changes in test strategy (i.e., changes in net braking and propulsive force production, braking depth, and GCT) [184], and without sufficient reliability being demonstrated in strategy metrics, only mean propulsive force can reliably explain changes acute change in net propulsive impulse in youth soccer players.

A limitation to the data collection in "study b" and "study c" was that the samples were not familiar with the specific test, having never performed it previously in a testing session. Whether an increase in familiarisation with test might improve the reliability of RJ portion ratio, strategy and kinetic metrics is unknown, which raises the opportunity for this to be assessed in a test-retest repeated measures design over a period of consecutive weeks. Future research should assess whether the reliability of RJ portion metrics in youth soccer players improves over time with more familiarity with the test. An additional layer of confliction with the CMRJ test is that the achievement of a consistent preliminary CMJ TOV and JH is also reliant on optimal NMF in the CMJ portion, which hypothetically could also reduce following neuromuscular fatigue. This would create an issue in monitoring RJ portion metrics following neuromuscular fatigue (e.g., pre to post match) because athletes could be subject to a different RJ portion fall heights on each testing occasion. Although changes in CMJ portion TOV can be reliably monitored using the MDCs presented in this study, this adds another layer of complexity to the interpretation of results which might make the test too complex for its use in the monitoring of acute changes in NMF. Based on these findings and considerations, it might be more prudent to advise the technically less complex and more easily applicable CMJ test.

7.5.3 Drop Jump

To the author's knowledge, "study b" is the first to report the test-retest reliability of the DJ test in youth soccer players in the pre-season period. Despite its common use as an assessment of fast SSC capacity, previous methods of DJ testing have faced scrutiny in recent literature [171]. The primary reason for its inclusion in this study is to compare the reliability of metrics in the DJ test to those of the RJ portion of the CMRJ test, in youth soccer players in the pre-season period. Like the RJ phase of the CMRJ, only net braking impulse (and body weight) demonstrated acceptable absolute and relative reliability (Table 7.5). This comprised of only three metrics (i.e., net braking impulse, body weight, and FT) demonstrating acceptable absolute reliability, and only two metrics demonstrating acceptable relative reliability (i.e., net braking impulse and body weight). Additionally, the box height inputted into the proprietary software was utilised to determine touch-down velocity, multiplied by body mass to determine landing momentum, and then used to permit the calculation of net braking impulse, and as discrepancies between box height and fall height (e.g., -31.5% fall height from 20 cm box height and -33.5% fall height from 40 cm box height [170]) have been reported in previous research utilising the DJ test [169-171], one could assume that the reliability of net braking impulse could have differed had the fall height been equated (which is not done via the proprietary software). Resultantly, as was the case for the RJ portion of the CMRJ, one could assume that the DJ test seemingly provides a poor ability to monitor changes in NMF in youth soccer players in the pre-season period. The potential differences between box height and fall height might also have contributed to the poor reliability in DJ metrics, but this was not assessed in this study directly. It is apparent again that homogeneity may be present with the relative reliability of measures in this cohort being seemingly poor [206]. Relative reliability might be improved in youth soccer players by improving absolute reliability in key metrics through familiarisation with the task, and potentially reducing homogeneity through developing physical capacity (which will happen at different rates amongst youth athletes) [36]. Thus, future research may assess whether the reliability of DJ metrics in youth soccer players improves over time (i.e., from pre- to in-season) and with more test familiarity.

7.5.4 Isometric Mid-Thigh Pull

The IMTP provides a testing option which can avoid within-subject differences in strategy with a standardised setup, and would theoretically produce less muscle damage over time as opposed to a RJ or DJ test which involves high eccentric loading [287]. Musham et al. [270] assessed youth soccer players with no prior experience with the IMTP, reporting acceptable reliability in absolute peak force, but relative peak force and force at 100 ms did not present acceptable absolute or relative reliability based on the 95% CIs. Dos'Santos et al. [189] assessed youth soccer players who were familiar with the IMTP protocol and had 6–12 months resistance training experience, and reported acceptable absolute and relative between-session reliability in peak force and force at 250 ms, but unacceptable reliability in force at 30, 50, 90, 100, 150, and 200 ms according to the CV% and ICC 95% CIs. The findings of "study b" are similar to these previous findings [189, 270], where peak force demonstrated the best absolute reliability out of the 12 metrics assessed, which was good based on the CV% (6.27%) and the +95% CI (9.98%). However, peak force demonstrated poor relative reliability in this cohort (Table 7.6), and resultantly, acceptable absolute and relative reliability was demonstrated in none of the twelve IMTP metrics, based on the 95% CIs, in youth soccer players in the pre-season period.

Comfort et al. [187] produced standardised protocols for implementation of the IMTP test, where it was suggested that although the optimal amount of familiarisation of the test has not yet been investigated, some form of familiarisation (e.g., a short session of submaximal trials approximately 48 hours before testing) should be provided prior to an IMTP testing session. Along these lines, Musham et al. [270] reported that the absolute and relative reliability of IMTP metrics improved every week over four consecutive weeks (one testing session per week) in youth soccer players. Similar to the population of Musham et al. [270], this study was conducted with youth soccer players who had little to no prior experience with the IMTP test, and testing was reflective of what occurs in real-world practice in youth soccer where it was conducted on the first and eighth day of pre-season, players were coming from a six-to-eight-week off-season with no scheduled training, and resultantly had no familiarisation session prior to the test-retest data collection. Thus, the lack of reliability in this cohort might be reflective of a lack of familiarity with the IMTP test, or a lack of training status as poor reliability has also been reported in this cohort in key CMRJ and DJ metrics (Tables 7.3 to 7.5). However, as other studies have also demonstrated poor reliability in key IMTP metrics as described above [189, 270], this may also just be a reflection of the performance of the IMTP test itself in youth soccer players, which could be due to poor absolute and relative strength levels. Based on the information presented in "study b", the IMTP test seems unreliable for the monitoring of acute changes in NMF in youth soccer players in the pre-season period, where additional familiarisation and increases in training status may be needed to achieve acceptable reliability [270]. Future research may assess the test-retest reliability of the IMTP test in youth soccer players over a period of weeks (potentially from pre- to in-season) to assess the effects of familiarity and potential changes in physical capacity on both absolute and relative reliability measures.

7.6 CONCLUSIONS

The results of "study a" demonstrate that all outcome metrics (N = 4 out of 4), 50% of the propulsive phase kinetic metrics (N = 7 out of 14), and none of the ratio or strategy metrics demonstrated acceptable absolute and relative reliability for the CMJ test in professional soccer players in the pre-season period. Overall, acceptable absolute and relative reliability was demonstrated in 13 CMJ metrics; bodyweight, peak velocity, jump momentum, FT, TOV, mean propulsive velocity, peak propulsive power, JH, mean propulsive force, mean propulsive power, peak braking force, force at minimum displacement, and peak propulsive force. Like the findings of "study a", the results of "study b" indicate that acceptable absolute and relative reliability was demonstrated in five CMJ metrics in youth soccer players in the pre-season period; body weight, jump momentum, peak propulsive power, mean propulsive force, and mean propulsive power (Table 7.2). Additionally, CMJ strategy (N = 5) and ratio (N = 3) measures also did not demonstrate acceptable reliability for youth soccer players in the pre-season period cohort. Thus, practitioners may consider a combination of these CMJ metrics for monitoring acute changes in NMF in soccer players from the youth to professional levels in the pre-season period (refer to Table 7.10). The results of "study c" indicate that acceptable absolute and relative reliability was demonstrated in 15 CMJ metrics in youth soccer players in the in-season period; bodyweight, peak velocity, TOV, jump momentum, FT, mean propulsive velocity, mean propulsive force, peak propulsive power, JH, mean propulsive power, propulsive phase time, net braking impulse, net impulse ratio, peak propulsive force, and countermovement depth. Practitioners may consider a combination of these CMJ metrics for monitoring acute changes in NMF in youth soccer players in the in-season period (refer to Table 7.10).

The reliability of the CMJ portion of the CMRJ test was like the CMJ test in "study b", with metrics such as body weight, peak propulsive power, jump momentum, and mean propulsive force demonstrating acceptable reliability. A mean difference of 2 cm (17.48%) in CMJ portion JH between weeks resulted in unacceptable reliability, but this was comparable to CMJ JH which also demonstrated unacceptable reliability, and less than previously reported discrepancies between DJ box height and fall height from 20 cm (-31.5%) and 40 cm (-33.5%) box heights [170]. Despite this, net braking impulse demonstrated acceptable reliability in the RJ portion of the CMRJ test, evidencing a consistent fall height in the RJ portion. Additionally, in "study c", acceptable absolute and relative reliability was demonstrated in bodyweight and outcome measures such as TOV, JH, and jump momentum (i.e., limited variability in fall height in the RJ portion) the CMJ portion of the CMRJ test, which means the test can be considered as an alternative to DJ test for the assessment of fast SSC in youth soccer players in the in-season period. However, monitoring options in RJ portion metrics were limited, with only net braking impulse, net impulse ratio, FT, jump momentum, TOV, and mean propulsive force demonstrating acceptable reliability. The complexity of performing the CMRJ test, which likely reduced the reliability of the RJ portion, also means it might hold less utility than the CMJ test for monitoring acute changes in NMF. If the use of a test of fast SSC capacity for monitoring acute changes in NMF is essential, practitioners can consider the listed RJ portion metrics as reliable options for the monitoring of changes in NMF in youth soccer, when data is collected in the in-season period. Practitioners must also consider the potential for the effects that an acute reduction in NMF could have on CMJ portion outcome, where variability in fall heights due to fatigue would directly affect RJ portion performance and reduce the utility of the test for monitoring acute changes in NMF.

Only net braking impulse demonstrated acceptable reliability in the DJ test, with comparable CVs (5.68% vs 2.70%, respectively) and ICCs (0.85 vs 0.92, respectively) to the RJ portion of the CMRJ test. Similarly, no IMTP metrics demonstrated acceptable reliability where only peak force demonstrated the acceptable absolute reliability (like the findings of previous studies [189, 270]) but poor relative reliability in this cohort (Table 7.6). The lack of reliability across tests in "study b" might be reflective of a lack of familiarity with the tests or a lack of training status within the cohort. Data collection in all studies within this chapter were reflective of what occurs in real-world practice in professional and youth soccer, where it was conducted on the first and eighth day of either a pre- or in-season formative evaluation period, and in the pre-season period players were coming from a six-to-eight-week off-season with no scheduled training and had no familiarisation session prior to the test-retest data collection. Comfort et al. [187] recommend some form of familiarisation prior to a force plate testing session, and Musham et al. [270] reported that the absolute and relative reliability of IMTP metrics improved every week over four consecutive weeks (one testing session per week) in youth soccer players.

Relative reliability was unacceptable across most CMJ (N = 19), RJ portion (N = 16), DJ (N = 19), and all IMTP (N = 12) metrics in "study b", which could be an issue with the homogeneity of physical capacity in youth athletes which affects the ranking of scores [206], and raises a question around the suitability of relative reliability measures in determining the reliability of force plate metrics, particularly in youth soccer players. Relative reliability might also be improved in youth soccer players by improving absolute reliability in key metrics through familiarisation with the tests, and potentially reducing homogeneity through developing physical capacity (which will happen at different rates amongst youth athletes) [36]. Thus, future research should assess the test-retest reliability of CMJ, CMRJ, DJ, and IMTP test variables in youth soccer players over a period of consecutive weeks (potentially from pre- to in-season) to assess the effects of familiarity and potential changes in physical capacity on both absolute and relative reliability measures. Researchers should also always interpret reliability results based on the 95% CIs of the CV% and ICC, rather than just the point-estimate values alone. Finally, monitoring changes in bodyweight independently must always be considered to provide information regarding whether changes in key outcome and kinetic measures were due to independent changes in NMF or bodyweight, or a combination of both [15, 184, 288].

Table 7.10. Summary Table Highlighting Which Variables Demonstrated Test-Retest Reliability and can be Considered for Monitoring Acute Changes in Neuromuscular Function.

Test		**Countermovement Jump**			**Countermovement Rebound Jump**
Cohort		**Professional**	**Youth**	**Youth**	**Youth**
Time		**Pre-Season**	**Pre-Season**	**In-Season**	**In-Season**
Ratio				Net Impulse Ratio	
Outcome		Jump Height		Jump Height	
		Flight Time		Flight Time	Flight Time
		Jump Momentum	Jump Momentum	Jump Momentum	Jump Momentum
		Takeoff Velocity		Takeoff Velocity	Takeoff Velocity
Propulsive		Mean Propulsive Power	Mean Propulsive Power	Mean Propulsive Power	
		Peak Propulsive Power	Peak Propulsive Power	Peak Propulsive Power	
		Peak Velocity		Peak Velocity	
		Mean Propulsive Velocity		Mean Propulsive Velocity	
		Mean Propulsive Force	Mean Propulsive Force	Mean Propulsive Force	Mean Propulsive Force
		Peak Propulsive Force		Peak Propulsive Force	
				Propulsive Phase Time	
Braking		Force at Minimum Displacement			
				Countermovement Depth	
				Net Braking Impulse	Net Braking Impulse
		Peak Braking Force			
Other					Jump Height (Countermovement Jump Portion)
		Bodyweight	Bodyweight	Bodyweight	Bodyweight

EXPERIMENTAL STUDY 3

8 NORMATIVE DATA AND OBJECTIVE BENCHMARKS OF FORCE PLATE TESTS FOR PROFESSIONAL AND YOUTH SOCCER PLAYERS IN THE ENGLISH FOOTBALL LEAGUE

8.1 INTRODUCTION

Force plates are among the most popular biomechanical apparatus used by physical preparation practitioners in sports (e.g., sports scientists, physiotherapists, etc.) to evaluate an athletes' NMF [161]. This is likely due to the development of more affordable and commercially available force plate systems, which have been validated against industry gold standard systems [21]. Evaluating soccer players' NMF can contribute to goal setting for training [11] and talent ID. The CMJ test is the most popular test to assess longitudinal developments in NMF in the football codes [23]. It is employed as a measure of ballistic "slow" SSC capacity [165]. Intuitively, outcome metrics (e.g., JH) [115], are often considered key metrics for profiling [115]. However, it is also important to understand what causes the outcome [115], with kinetic (e.g., absolute and relative mean and peak propulsion force and power), and strategy (e.g., braking and propulsion time and countermovement depth) metrics identified as most related to the outcome of the CMJ test [32].

The CMJ test requires minimal familiarisation, is quick to perform, and is relatively non-fatiguing, meaning outcome and strategy metrics have demonstrated good between-trial reliability (CV ≤ 10%) (as evidenced in chapter 7) [65-67]. Variations of RJ tests [61, 67, 174] are used as measures of plyometric "fast" (i.e., <250 ms) SSC capacity, and lower-body reactive strength qualities in the football codes [23]. The correct execution of "fast" SSC tests requires a greater degree of technical competency and neuromuscular capacity, which might explain why research has identified a high degree of between-trial variability (CV > 10%) in RJ ratio metrics such as the RSI (as evidenced in chapter 7), which could render the metric insensitive to detecting meaningful changes in NMF [67, 168]. Additionally, examples such as the DJ test require additional equipment (i.e., a box to drop from), and large discrepancies (±20%) have been reported between box height and actual fall height (as evidenced in chapter 6) [21, 171], which can lead to erroneous measures of NMF if not accounted for [67, 168].

The CMRJ, which consists of a preliminary CMJ followed by a single RJ, requires no additional equipment to conduct the test, and the RJ fall height (i.e., preliminary CMJ height) has demonstrated acceptable absolute and relative between-session reliability in youth soccer players (as evidenced in section 7.10.2) [58]. Xu et al. [173] also identified acceptable absolute and relative reliability in CMJ portion metrics such as JH, countermovement depth, time to take-off, and RJ portion GCT. This was comparable to reports seen in the DJ test, and the authors offered the CMRJ as a potential alternative to the DJ test after reporting consistent hip, knee, and ankle joint work between the tests [173]. The IMTP test is commonly employed to evaluate lower body "strength" [188-190]. It is considered safer, less fatiguing, and more practically feasible than dynamic repetition maximum testing [187]. A standardised set-up can also be used to avoid within-participant differences in technique [187]. Acceptable absolute and relative reliability within- and between-sessions have been identified in male youth soccer players for measures such as peak force and force at various time-points (e.g., 50, 100, 150, 200, and 250 ms) [189].

The primary purpose of evaluating soccer athletes' NMF is talent ID and goal setting for training [11]. Published normative data studies are available to help with this process [27, 37-39] however, often the data only represents the average of the population used and does not provide a determination of what is a "good" performance within a cohort [40]. Although this can be determined via the mean and SD of reported measures, the sample sizes utilised in previous normative data research in soccer [37-39] have been smaller than recommended for normative data research (i.e., 85 participants [207]), where larger sample sizes would provide greater accuracy and a better representation of the mean of a population, and as a result would add strength to research in this area [318]. A targeted approach to sampling enough subjects within future normative data research will provide confidence in a study's results. McMahon et al. [114] presented a novel approach to compiling and presenting normative data via the creation of "objective benchmarks" [114], utilising a grading system of standardised T-scores (scaled from 0 to 100), qualitative description (ranging from extremely poor to excellent), and a colour coded system to enhance interpretation. It is advised that published normative data should only be used within comparable groups [30], and objective benchmarks (i.e., goal setting) cannot be prescribed for key tests and metrics without the existence of cohort-specific normative data sets [114]. Thus, it seems rational to consider that normative data and objective benchmarks for professional and youth soccer players across a range of force plates tests of NMF specific to every competitive league would be useful.

For a measure to hold utility as an objective benchmark, it must discriminate between groups of interest (e.g., different competitive levels and/or age categories). Emmonds et al. [38] presented physical characteristics of female youth soccer players across multiple chronological age groups (U10, U12, U14 and U16) within the academy of a professional English football club, identifying a small to large (Hedge's g = 0.41 to 1.05) increase in CMJ height across each respective age group [38]. From these findings, one could deduce that relative propulsive impulse in "slow" (i.e., >250 ms) SSC tasks increases with age in female youth soccer players, despite a concurrent increase in body mass [37, 38]. As only JH was reported in the studies by Emmonds et al. [37, 38], it is unclear whether the increases in JH (i.e., outcome) were caused by changes in mean propulsion force (i.e., kinetic) or propulsion phase time (i.e., strategy). Emmonds et al. [38] also revealed large (Hedge's g = 0.81 to 1.47) increases in IMTP peak force, but trivial to small (Hedge's g = 0.06 to 0.24) differences in relative peak force, across chronological age groups in female youth soccer players. Similarly, Morris et al. [39] identified significant differences ($p < 0.05$) in IMTP peak force across consecutive age groups (U12 through U18) in male youth professional soccer players, but less of a difference in relative peak force [39]. Morris et al. [39] only utilised the IMTP test so no comparisons could be made to CMJ results reported by Emmonds et al. [37, 38]. This leaves a distinct gap in information for football practitioners who regularly utilise force plate tests with their athletes. It is currently unknown how NMF characteristics compare between youth and professional soccer players which would help to inform physical preparation priorities for athletes transitioning from U18 to professional level like has been done somewhat in rugby league [27].

The aim of this study was to establish normative data and objective benchmarks for key CMJ, CMRJ, and IMTP metrics in professional and youth soccer players in the EFL League 2 and investigate age-specific statistical differences between groups. According to the EPPP, EFL academies are typically structured to include a full-time "YT" (U17 to U18) scholarship programme where players are evaluated over the course of 2 seasons for the potential to be offered professional contracts [201]. Accordingly, soccer players who were part of the "YT" and those who held professional contracts are referred to in this study as "youth" and "professional" soccer players, respectively. To the authors' knowledge, such a study has not yet been performed within any professional football league worldwide. Based on the results presented in previous similar studies in soccer [37-39], an overlap of individual scores is expected between age groups, however, it was hypothesised that professional soccer players would produce significantly greater outcome performances (e.g., JH) in both jump tasks through the greater expression of relative kinetic output, but through similar movement strategies. It was also hypothesised that IMTP absolute, but not relative, peak force would be greater for professional soccer players, in line with previous findings [37-39].

8.2 METHODS

This study was pre-approved by the University of Salford institutional review board and conformed to the World Medical Association's Declaration of Helsinki 2013. The data collection for this study was conducted over three consecutive EFL pre-seasons, specifically, the 2021/22, 2022/23, and 2023/24 seasons. All participants provided written informed consent or parental assent, as appropriate. Participants were only included within the study sample once. If the same participant was tested across multiple pre-seasons, the most recent test results were utilised.

8.2.1 Participants

For the groups comparisons (i.e., professional vs. youth), a sample size requirement estimation was performed using G*Power (Dusseldorf, Germany) [319, 320]. Researchers have reported an average ES of 0.58 (moderate) and 0.82 (large) across age group comparisons for CMJ JH [37] and IMTP peak force [39], respectively. The average of these two ESs is equal to a moderate ES of 0.70. An *a priori* sample size estimation for independent T-Test, with an expected moderate ES of 0.70, and an alpha level of 0.05, indicated the minimum sample size required to yield a statistical power of 0.95 was 90 (45 per group) participants. Previous research has estimated that sample sizes of greater than 85 (per group) are required to produce normative data, to generate stable means and SDs regardless of the degree of skewness in the dataset [207]. The researchers aimed to collect data on a minimum of 85 participants per group for this study to satisfy these recommendations [207].

A targeted sampling approach led to 7 professional EFL clubs being recruited for this study, from which athletes were employed as a soccer player on a full-time basis, in the EFL 2 or EFL youth alliance league (EFL academy categories 2 to 4) competitions, respectively, at the time of testing. Based on the participant classification framework produced by McKay et al. [164], these participants would represent tier 4: elite (professional) and tier 3: highly trained (youth). From these clubs, the sample sizes for each test, the sample size in relation to the maximum number of players available to be registered in the league each season (as a percentage), and participant characteristics are illustrated in Table 8.1. All participants had previous experience performing VJ and IMTP tasks on force plates in training and previous physical performance testing and were free from injury at testing (pre-season).

Table 8.1. Sample sizes for the professional and youth populations.

	CMJ	CMRJ	IMTP	Age (years)	Height (cm)	Mass (kg)
1st Team	139	136	137	24 ± 5	184 ± 7	81 ± 9
% of League	26	26	26			
Youth Team	137	135	121	17 ± 1	178 ± 17	72 ± 8
% of League	26	26	23			

Key: CMJ, Countermovement Jump; CMRJ, Countermovement Rebound Jump; IMTP, Isometric Mid-Thigh Pull.

8.2.2 Procedures

A full description of data collection procedures for the CMJ, CMRJ, and IMTP tests can be found in Chapter 5 titled "General Methods".

8.2.3 Data analysis

Data analysis was automatically performed after each trial via the HD Inc. proprietary software. A full description of data analysis procedures including the start of numerical integration and phase descriptions for the CMJ, CMRJ, and IMTP tests can be found in chapter 5 General Methods. Variable definitions for the CMJ, CMRJ, and IMTP tests can also be found in chapter 5 General Methods in tables 5.1, 5.2, and 5.3, respectively. All relative kinetic metrics reported in this study are relative to bodyweight (i.e., N/bw).

8.2.4 Statistical analyses

Data Distribution. A Shapiro-Wilk test was performed to determine if the data satisfied the assumptions of normal distribution [210, 304]. It has been proposed that formal normality tests (e.g., the Shapiro-Wilk test) can be used from small to medium sized sample sizes (e.g., $n < 300$) [211].

Descriptive Statistics. Descriptive statistics of central tendency (i.e., mean or median) and variability (i.e., SD or IQR) were calculated for each metric in each age category independently using a Microsoft Excel spreadsheet (version 16; Microsoft Corp., Redmond, WA, USA). This represents normative data for each age category. For between-group comparisons, the mean of each variable across the three recorded trials was taken forward for statistical analysis.

Relative Reliability. For the determination of within-session (between trial) relative (rank order) reliability of every metric, the values of each variable for the three individual trials were analysed using a two-way mixed-effects model (average measures) ICC along with the upper and lower 95% CI. The ICCs were interpreted as poor (≤0.49), moderate (0.50 to 0.74), good (0.75 to 0.89), and excellent (≥0.90) relative reliability, based on the lower-bound 95% CI of the ICC estimate [297].

Mean Difference. To compare mean differences between professional and youth data, an independent t-test was performed for each variable ($p < 0.05$) [114]. If the data did not satisfy the assumptions of normal distribution a non-parametric independent t-test (i.e., a Mann-Whitney U test) was performed for each variable ($p < 0.05$) [321]. Because the sample sizes in each group in this study were unequal, Hedge's g ESs were calculated with 95% CI to provide an inference of the magnitude of difference between groups. The ES were interpreted as trivial (≤0.19), small (0.20 to 0.49), moderate (0.50 to 0.79), or large (≥0.80) [214].

Objective Benchmarks. Before determining which measure of central tendency and variability was utilised to create objective benchmarks, the skewness and kurtosis were determined for select measures [304]. These measures included commonly reported metrics which demonstrated acceptable within-session reliability and a significant mean difference between groups, including mRSI, RSI, FT:CT, JH, FT, jump momentum, and mean and peak propulsive force and power, and relative mean and peak propulsive force and power (Appendix 6). A "Z-Test" was conducted to assess normality using skewness and kurtosis [211]. This was done by dividing the skew values or "excess" kurtosis (provided by most statistical packages, e.g., SPSS) by their standard errors [211]. As the sample size in this study was classified as 'medium-sized' (N = 50 to 300), an absolute z-value of over 3.29 ($p < 0.05$) was prescribed to conclude the distribution of the data in this sample as non-normal [211]. The tests of reliability, data distribution, mean difference, and skewness and kurtosis were conducted in SPSS (version 29; SPSS Inc., Chicago, IL, USA).

The mean and SD of each measure was utilised to create the objective benchmark, unless the data reported skewness and kurtosis where the median and IQR were instead utilised [304]. To create the objective benchmarks, multiples of the SD of a mean value were multiplied by standardised "Z-Scores" (see Table 8.2) and added to the mean value, as described in the following formula:

$$\text{Mean Value} + (\text{SD} * \text{Corresponding Z-Score})$$

[114].

Additionally, "T-Scores" were calculated to help with the interpretation of scores (see Table 8.2), utilising the following formula:

$$(\text{Z-Score Value (e.g., -3)} * 10) + 50$$

[114].

As done in recent similar research by McMahon et al. [114], these T-Scores are reported alongside qualitative descriptions to grade and qualitatively interpret the calculated objective benchmarks (see Table 8.2). All information gained for the objective benchmarks was produced using an Excel spreadsheet (version 16; Microsoft Corp., Redmond, WA, USA).

Table 8.2. Corresponding Z-Score, T-Score, and Qualitative Descriptors.

Z-Score			T-Score			Grade
> 3.0			> 80			Excellent
2.0	to	3.0	70	to	80	Very Good
1.0	to	2.0	60	to	70	Good
0.5	to	1.0	55	to	60	Above Avg.
0.0	to	0.5	50	to	55	Average (Avg.)
-1.0	to	-0.5	40	to	45	Below Avg.
-2.0	to	-1.0	30	to	40	Poor
-3.0	to	-2.0	20	to	30	Very Poor
< -3.0			< 20			Extremely Poor

8.3 RESULTS

Descriptive statistics of central tendency, variability, and within-session relative reliability for professional and youth soccer players are presented for the CMJ test (Table 8.3), CMJ portion (Table 8.5) and RJ portion (Table 8.6) of the CMRJ test, and the IMTP test (Table 8.8). All metrics demonstrated good to excellent within-session relative reliability for both professional and youth soccer players for all tests.

8.3.1 Age comparisons

All CMJ metric values were significantly greater for professional vs youth soccer players, except time to take-off, net impulse ratio, propulsive phase time, countermovement depth, relative peak braking power, relative mean braking force, and braking phase time (Table 8.3). All CMRJ metric values were significantly greater for professional vs youth soccer players, except CMJ portion time to take-off (Table 8.5), and RJ portion GCT, relative peak propulsive power, relative mean propulsive force, relative peak propulsive force, and relative peak braking force (Table 8.6). IMTP metric values were significantly greater for professional vs youth soccer players (Table 8.8).

8.3.2 Objective benchmarks

Skewness and kurtosis of metrics can be found in supplementary information S6. In the CMJ test, skewness was identified in metrics such as mRSI, FT:CT, and relative mean propulsive force in professional soccer players, and peak propulsive force and relative peak propulsive force in both professional and youth soccer players. Kurtosis was identified in FT:CT for professional soccer players, peak propulsive force for youth soccer players, and relative peak propulsive force for both professional and youth soccer players. In the CMRJ test, only skewness was identified in RJ portion FT:CT in professional soccer players. In the IMTP test, neither skewness nor kurtosis were identified. Consequently, the median and IQR was utilised to create the objective benchmarks only for three CMJ metrics, which included FT:CT in professional soccer players, peak propulsive force in youth soccer players, and relative peak propulsive force in both professional and youth soccer players. The objective benchmarks for professional and youth soccer players are presented for the CMJ test (Table 8.4), RJ portion of the CMRJ test (Table 8.7), and the IMTP test (Table 8.9). *Alternative presentation of objective benchmarks for select variables can be found in supplementary information S7.*

Table 8.3. Countermovement Jump Descriptive Statistics and Reliability (Professional and Youth Soccer Players).

CMJ Metrics	1st Team					Youth Team					Comparison			
	AVG	DIS	ICC (95% CI)			AVG	DIS	ICC (95% CI)			T-Test	ES (95% CI)		
mRSI (AU)	0.56	0.13	0.919	0.891	0.941	0.51	0.10	0.880	0.839	0.911	$0.001^{\dagger}$	0.443	0.221	0.660
FT:CT (AU)	0.80 $^{\tilde{x}}$	0.19	0.892	0.855	0.921	0.79	0.13	0.851	0.801	0.890	0.021	0.315	0.090	0.535
Jump Height (m)	0.38	0.05	0.977	0.966	0.984	0.35	0.05	0.970	0.957	0.978	$<0.001^{\dagger}$	0.658	0.404	0.905
Flight Time (s)	0.57	0.03	0.970	0.943	0.982	0.54	0.04	0.972	0.960	0.980	$<0.001^{\dagger}$	0.752	0.490	1.014
Jump Momentum (kg·m/s)	222.64	27.77	0.994	0.992	0.996	188.49	27.57	0.992	0.989	0.995	<0.001	0.848	0.652	1.042
Takeoff Velocity (m/s)	2.74	0.17	0.977	0.966	0.984	2.62	0.18	0.968	0.955	0.977	<0.001	0.490	0.313	0.666
Time to Take-off (s)	0.72	0.12	0.858	0.809	0.896	0.71	0.11	0.837	0.782	0.880	0.787	0.023	-0.144	0.190
Relative Mean Propulsive Power (W/bw)	3.47	0.53	0.982	0.975	0.987	3.20	0.41	0.946	0.927	0.960	$<0.001^{\dagger}$	0.564	0.337	0.791

Mean Propulsive Power (W)	2754.21	442.65	0.984	0.978	0.989	2253.78	400.57	0.971	0.961	0.979	<0.001	0.892	0.693	1.088
Relative Peak Propulsive Power (W/bw)	5.83	0.79	0.987	0.982	0.990	5.48	0.59	0.955	0.940	0.967	<0.001	0.365	0.192	0.536
Peak Propulsive Power (W)	4632.00	690.40	0.989	0.986	0.992	3861.48	625.02	0.980	0.973	0.985	<0.001	0.874	0.677	1.069
Peak Velocity (m/s)	2.84	0.17	0.977	0.967	0.984	2.73	0.17	0.969	0.955	0.978	<0.001	0.476	0.299	0.651
Mean Propulsive Velocity (m/s)	1.70	0.11	0.969	0.948	0.981	1.62	0.11	0.940	0.913	0.959	<0.001	0.492	0.315	0.668
Net Impulse Ratio (AU)	2.14	0.33	0.900	0.858	0.929	2.08	0.28	0.886	0.844	0.917	0.188[†]	0.207	-0.028	0.440
Relative Mean Propulsive Force (N/bw)	2.29	0.30	0.979	0.972	0.985	2.20	0.22	0.937	0.916	0.954	0.016[†]	0.334	0.110	0.558
Mean Propulsive Force (N)	1817.06	252.15	0.982	0.975	0.987	1546.94	227.34	0.969	0.959	0.977	<0.001	0.829	0.635	1.022
Relative Peak Propulsive Force (N/bw)	2.77 [x̃]	0.62	0.972	0.963	0.980	2.65 [x̃]	0.49	0.917	0.890	0.939	0.030[†]	0.270	0.035	0.493
Peak Propulsive Force (N)	2306.90	441.73	0.970	0.959	0.978	1905.67 [x̃]	426.25	0.940	0.920	0.956	<0.001[†]	0.869	0.613	1.110
Propulsive Phase Time (s)	0.23	0.05	0.976			0.23	0.04	0.948			0.536[†]	0.094		

				0.968	0.983				0.931	0.962			-0.333	0.128
Countermovement Depth (m)	0.28	0.07	0.970	0.958	0.978	0.28	0.07	0.943	0.924	0.958	0.471†	0.100	-0.335	0.143
Braking RFD (N/s)	12553.80	9469.19	0.969	0.958	0.978	9557.86	7058.84	0.906	0.875	0.931	<0.001†	0.357	0.075	0.566
Relative Mean Braking Power (W/bw)	1.58	0.34	0.938	0.890	0.962	1.50	0.32	0.912	0.879	0.937	0.027†	0.241	0.000	0.484
Mean Braking Power (W)	1265.20	311.42	0.951	0.911	0.970	1064.12	278.20	0.935	0.910	0.953	<0.001†	0.679	0.423	0.927
Relative Peak Braking Power (W/bw)	2.21	0.61	0.930	0.888	0.955	2.13	0.60	0.885	0.845	0.915	0.176†	0.128	-0.120	0.367
Peak Braking Power (W)	1767.70	529.21	0.939	0.901	0.961	1510.61	475.02	0.904	0.872	0.930	<0.001†	0.510	0.264	0.745
Net Braking Impulse (N.s)	107.65	22.06	0.963	0.939	0.977	93.38	19.34	0.954	0.934	0.968	<0.001†	0.686	0.434	0.925
Relative Mean Braking Force (N/bw)	2.06	0.37	0.957	0.935	0.971	1.99	0.30	0.918	0.890	0.939	0.121†	0.193	-0.046	0.433
Mean Braking Force (N)	1637.73	314.04	0.962	0.942	0.975	1405.27	275.61	0.945	0.926	0.959	<0.001†	0.784	0.536	1.035
Relative Peak Braking Force (N/bw)	2.84	0.62	0.972	0.958	0.981	2.67	0.47	0.912	0.883	0.935	0.013†	0.297	0.065	0.516

Peak Braking Force (N)	2251.82	476.47	0.970		1883.73	400.74	0.936		<0.001†	0.833	
			0.955	0.980			0.915	0.953		0.575	1.066
Braking Phase Time (s)	0.14	0.04	0.930		0.14	0.03	0.911		0.669	0.036	
			0.906	0.949			0.881	0.934		-0.203	0.130
Body Weight (N)	797.58	89.02	1.000		703.94	81.29	1.000		<0.001	0.726	
			1.000	1.000			1.000	1.000		0.537	0.912

Key: CMJ, countermovement jump; AVG, average; DIS, distribution; ICC, intraclass correlation coefficient; dark green cell shading, excellent reliability; bright green cell shading, good reliability; ES, effect size; mRSI, modified reactive strength index; FT:CT, flight time CMRJ ratio; AU, arbitrary unit; m, metres; s, seconds; kg, kilograms; W, watts; N, Newtons; bw, bodyweight; x̃, median and interquartile range reported; †, denotes Mann-Whitney U test used.

Table 8.4. Countermovement Jump Metrics Objective Benchmarks (Professional and Youth Soccer Players).

OBJECTIVE BENCHMARKS										
CMJ Metrics	**Group**	**Excellent**	**Very Good**	**Good**	**Above Avg.**	**Average (Avg.)**	**Below Avg.**	**Poor**	**Very Poor**	**Extremely Poor**
mRSI (AU)	1st Team	**0.93**	**0.81**	**0.68**	**0.62**	**0.56**	**0.50**	**0.43**	**0.31**	**0.18**
	Youth Team	**0.80**	**0.70**	**0.60**	**0.56**	**0.51**	**0.46**	**0.41**	**0.32**	**0.22**
FT:CT (AU)	1st Team	**1.36**	**1.17**	**0.99**	**0.90**	**0.80**	**0.71**	**0.62**	**0.43**	**0.25**
	Youth Team	**1.17**	**1.04**	**0.91**	**0.85**	**0.79**	**0.72**	**0.66**	**0.53**	**0.40**
Jump Height (m)	1st Team	**0.53**	**0.48**	**0.43**	**0.41**	**0.38**	**0.36**	**0.34**	**0.29**	**0.24**
	Youth Team	**0.50**	**0.45**	**0.40**	**0.38**	**0.35**	**0.33**	**0.30**	**0.25**	**0.21**
Flight Time (s)	1st Team	**0.67**	**0.64**	**0.60**	**0.59**	**0.57**	**0.56**	**0.54**	**0.51**	**0.47**
	Youth Team	**0.67**	**0.62**	**0.58**	**0.56**	**0.54**	**0.52**	**0.50**	**0.46**	**0.42**
Jump Momentum (kg·m/s)	1st Team	**306**	**278**	**250**	**237**	**223**	**209**	**195**	**167**	**139**
	Youth Team	**271**	**244**	**216**	**202**	**188**	**175**	**161**	**133**	**106**
	1st Team	**5.06**	**4.53**	**4.00**	**3.73**	**3.47**	**3.20**	**2.94**	**2.41**	**1.88**

Relative Mean Propulsive Power (W/bw)	Youth Team	4.44	4.03	3.61	3.41	3.20	2.99	2.79	2.37	1.96
Relative Peak Propulsive Power (W/bw)	1st Team	8.20	7.41	6.62	6.23	5.83	5.44	5.04	4.25	3.46
	Youth Team	7.26	6.67	6.07	5.78	5.48	5.19	4.89	4.30	3.71
Relative Mean Propulsive Force (N/bw)	1st Team	3.19	2.89	2.59	2.44	2.29	2.14	1.99	1.69	1.39
	Youth Team	2.87	2.65	2.42	2.31	2.20	2.09	1.97	1.75	1.53
Relative Peak Propulsive Force (N/bw)	1st Team	4.66	4.07	3.49	3.20	2.91	2.62	2.33	1.74	1.16
	Youth Team	4.12	3.63	3.14	2.90	2.65	2.41	2.16	1.67	1.18
Mean Propulsive Power (W)	1st Team	4082	3639	3197	2976	2754	2533	2312	1869	1426
	Youth Team	3455	3055	2654	2454	2254	2053	1853	1453	1052
Peak Propulsive Power (W)	1st Team	6703	6013	5322	4977	4632	4287	3942	3251	2561
	Youth Team	5737	5112	4486	4174	3861	3549	3236	2611	1986
Mean Propulsive Force (N)	1st Team	2574	2321	2069	1943	1817	1691	1565	1313	1061
	Youth Team	2229	2002	1774	1661	1547	1433	1320	1092	865

Peak Propulsive Force (N)	1st Team	**3632**	**3190**	**2749**	**2528**	**2307**	**2086**	**1865**	**1423**	**982**
	Youth Team	**3184**	**2758**	**2332**	**2119**	**1906**	**1693**	**1479**	**1053**	**627**

Key: CMJ, countermovement jump; mRSI, modified reactive strength index; FT:CT, flight time CMRJ ratio; AU, arbitrary unit; m, metres; s, seconds; kg, kilograms; W, watts; N, Newtons; bw, bodyweight.

Table 8.5. Countermovement Jump Portion Descriptive Statistics and Reliability (Professional and Youth Soccer Players).

CMJ Portion Metrics	1st Team				Youth Team				Comparison		
	AVG	DIS	ICC (95% CI)		AVG	DIS	ICC (95% CI)		T-Test	ES (95% CI)	
Jump Height (m)	0.35	0.05	0.932		0.31	0.05	0.936		<0.001†	0.810	
			0.901	0.953			0.913	0.953		0.561	1.045
Jump Momentum (kg·m/s)	211.35	25.45	0.977		175.11	24.00	0.969		<0.001	0.997	
			0.966	0.984			0.957	0.977		0.790	1.202
Time to Take-off (s)	0.623	0.121	0.889		0.604	0.107	0.893		0.136	0.128	
			0.849	0.92			0.854	0.922		-0.040	0.297
Countermovement Depth (m)	0.23	0.07	0.957		0.21	0.06	0.947		0.013†	0.340	
			0.938	0.97			0.928	0.961		0.087	0.571
Body Weight (N)	798.03	87.29	1.000		702.89	75.89	1.000		<0.001	0.789	
			1.000	1.000			1.000	1.000		0.596	0.981

Key: CMJ, countermovement jump; AVG, average; DIS, distribution; ICC, intraclass correlation coefficient; dark green cell shading, excellent reliability; bright green cell shading, good reliability; ES, effect size; m, metres; s, seconds; kg, kilograms; N, Newtons; †, denotes Mann-Whitney U test used.

Table 8.6. Rebound Jump Portion Descriptive Statistics and Reliability (Professional and Youth Soccer Players).

RJ Portion Metrics	1st Team				Youth Team				Comparison		
	AVG	DIS	ICC (95% CI)		AVG	DIS	ICC (95% CI)		T-Test	ES (95% CI)	
RSI (AU)	1.71	0.32	0.864		1.59	0.29	0.934		<0.001†	0.294	
			0.81	0.903			0.908	0.954		0.122	0.465
FT:CT (AU)	2.64	0.36	0.892		2.51	0.33	0.922		0.004	0.370	
			0.854	0.922			0.888	0.946		0.125	0.601
Jump Height (m)	0.35	0.06	0.892		0.32	0.05	0.949		<0.001	0.366	
			0.847	0.925			0.930	0.963		0.192	0.539
Flight Time (s)	0.54	0.04	0.923		0.51	0.05	0.945		<0.001†	0.738	
			0.886	0.948			0.924	0.96		0.488	0.979
Jump Momentum (kg·m/s)	212.93	26.10	0.951		179.96	24.68	0.973		<0.001†	1.295	
			0.931	0.966			0.964	0.981		1.002	1.576
Ground Contact Time (s)	0.21	0.02	0.88		0.21	0.02	0.913		0.276†	0.124	
			0.837	0.913			0.882	0.937		-0.115	0.370
Relative Mean Propulsive Power (W/bw)	5.02	0.72	0.933		4.79	0.63	0.927		0.005	0.245	
			0.905	0.953			0.899	0.936		0.074	0.415
Mean Propulsive Power (W)	3986.69	607.80	0.950		3364.84	549.34	0.955		<0.001	0.817	
			0.928	0.965			0.937	0.968		0.622	1.010

Relative Peak Propulsive Power (W/bw)	8.22	1.22	0.897	0.857	0.927	7.99	1.02	0.919	0.888	0.942	0.082	0.150	-0.019	0.319
Peak Propulsive Power (W)	6531.53	1021.52	0.914	0.88	0.939	5609.62	889.38	0.947	0.926	0.962	<0.001	0.733	0.542	0.921
Net Impulse Ratio (AU)	0.98	0.08	0.867	0.82	0.904	1.02	0.10	0.892	0.853	0.921	<0.001[†]	0.465	0.219	0.701
Relative Mean Propulsive Force (N/bw)	3.38	0.35	0.91	0.878	0.935	3.35	0.30	0.921	0.891	0.944	0.471	0.062	-0.106	0.230
Mean Propulsive Force (N)	2689.56	337.84	0.946	0.926	0.961	2354.03	301.42	0.962	0.947	0.973	<0.001	0.797	0.603	0.988
Relative Peak Propulsive Force (N/bw)	5.71	0.90	0.893	0.854	0.922	5.76	0.78	0.897	0.857	0.927	0.745[†]	0.060	-0.298	0.185
Peak Propulsive Force (N)	4540.83	767.95	0.91	0.878	0.935	4046.98	680.14	0.935	0.909	0.954	<0.001[†]	0.679	0.436	0.912
Braking Depth (m)	0.11	0.04	0.82	0.756	0.87	0.09	0.03	0.816	0.75	0.866	<0.001[†]	0.544	0.308	0.777
Relative Mean Braking Power (W/bw)	5.94	0.83	0.895	0.853	0.926	5.22	0.87	0.932	0.906	0.952	<0.001[†]	0.328	0.087	0.564
Mean Braking Power (W)	4735.90	815.11	0.93	0.902	0.951	3673.06	737.85	0.952	0.933	0.967	<0.001	0.989	0.783	1.193
	2.13	0.55	0.857			1.94	0.59	0.906			0.004[†]	0.694		

Relative Peak Braking Power (W/bw)				0.804	0.897				0.873	0.932			0.421	0.957
Peak Braking Power (W)	9115.54	1889.25	0.89	0.85	0.921	6966.01	1842.09	0.929	0.904	0.949	<0.001†	1.149	0.864	1.421
Net Braking Impulse (N.s)	219.06	27.88	0.975	0.962	0.983	177.71	24.71	0.973	0.963	0.98	<0.001	1.039	0.829	1.247
Relative Mean Braking Force (N/bw)	3.99	0.44	0.874	0.828	0.909	3.73	0.48	0.924	0.895	0.946	<0.001†	0.558	0.289	0.800
Mean Braking Force (N)	3184.83	481.99	0.936	0.913	0.954	2625.43	437.52	0.957	0.939	0.969	<0.001	0.876	0.677	1.073
Relative Peak Braking Force (N/bw)	6.66	0.90	0.828	0.767	0.876	6.45	0.95	0.888	0.846	0.92	0.052†	0.227	0.031	0.472
Peak Braking Force (N)	5309.87	863.70	0.886	0.846	0.918	4540.28	839.22	0.934	0.908	0.953	<0.001	0.650	0.464	0.834

Key: RJ, rebound jump; AVG, average; DIS, distribution; ICC, intraclass correlation coefficient; dark green cell shading, excellent reliability; bright green cell shading, good reliability; ES, effect size; RSI, reactive strength index; FT:CT, flight time CMRJ ratio; AU, arbitrary unit; m, metres; s, seconds; kg, kilograms; W, watts; N, Newtons; bw, bodyweight; †, denotes Mann-Whitney U test used.

Table 8.7. Rebound Jump Portion Metrics Objective Benchmarks (Professional and Youth Soccer Players).

OBJECTIVE BENCHMARKS										
RJ Portion Metrics	**Group**	**Excellent**	**Very Good**	**Good**	**Above Avg.**	**Average (Avg.)**	**Below Avg.**	**Poor**	**Very Poor**	**Extremely Poor**
RSI (AU)	1st Team	**2.68**	**2.36**	**2.04**	**1.88**	**1.71**	**1.55**	**1.39**	**1.07**	**0.74**
	Youth Team	**2.48**	**2.18**	**1.89**	**1.74**	**1.59**	**1.45**	**1.30**	**1.00**	**0.71**
FT:CT (AU)	1st Team	**3.71**	**3.35**	**2.99**	**2.82**	**2.64**	**2.46**	**2.28**	**1.92**	**1.57**
	Youth Team	**3.51**	**3.18**	**2.84**	**2.68**	**2.51**	**2.34**	**2.18**	**1.84**	**1.51**
Jump Height (m)	1st Team	**0.52**	**0.46**	**0.41**	**0.38**	**0.35**	**0.33**	**0.30**	**0.24**	**0.19**
	Youth Team	**0.49**	**0.43**	**0.38**	**0.35**	**0.32**	**0.30**	**0.27**	**0.22**	**0.16**
Flight Time (s)	1st Team	**0.66**	**0.62**	**0.58**	**0.56**	**0.54**	**0.52**	**0.50**	**0.46**	**0.42**
	Youth Team	**0.65**	**0.60**	**0.56**	**0.53**	**0.51**	**0.49**	**0.46**	**0.42**	**0.37**
Jump Momentum (kg·m/s)	1st Team	**291**	**265**	**239**	**226**	**213**	**200**	**187**	**161**	**135**
	Youth Team	**254**	**229**	**205**	**192**	**180**	**168**	**155**	**131**	**106**

Relative Mean Propulsive Power (W/bw)	1st Team	**7.17**	**6.45**	**5.73**	**5.37**	**5.02**	**4.66**	**4.30**	**3.58**	**2.86**
	Youth Team	**6.69**	**6.06**	**5.43**	**5.11**	**4.79**	**4.48**	**4.16**	**3.53**	**2.90**
Mean Propulsive Power (W)	1st Team	**5810**	**5202**	**4594**	**4291**	**3987**	**3683**	**3379**	**2771**	**2163**
	Youth Team	**5013**	**4464**	**3914**	**3640**	**3365**	**3090**	**2816**	**2266**	**1717**
Peak Propulsive Power (W)	1st Team	**9596**	**8575**	**7553**	**7042**	**6532**	**6021**	**5510**	**4488**	**3467**
	Youth Team	**8278**	**7388**	**6499**	**6054**	**5610**	**5165**	**4720**	**3831**	**2941**
Mean Propulsive Force (N)	1st Team	**3703**	**3365**	**3027**	**2858**	**2690**	**2521**	**2352**	**2014**	**1676**
	Youth Team	**3258**	**2957**	**2655**	**2505**	**2354**	**2203**	**2053**	**1751**	**1450**
Peak Propulsive Force (N)	1st Team	**6845**	**6077**	**5309**	**4925**	**4541**	**4157**	**3773**	**3005**	**2237**
	Youth Team	**6087**	**5407**	**4727**	**4387**	**4047**	**3707**	**3367**	**2687**	**2007**

Key: RJ, rebound jump; RSI, reactive strength index; FT:CT, flight time CMRJ ratio; AU, arbitrary unit; m, metres; s, seconds; kg, kilograms; W, watts; N, Newtons; bw, bodyweight.

Table 8.8. Isometric Mid-Thigh Pull Descriptive Statistics and Reliability (Professional and Youth Soccer Players).

IMTP Metrics	1st Team				Youth Team				Comparison		
	AVG	DIS	ICC (95% CI)		AVG	DIS	ICC (95% CI)		T-Test	ES (95% CI)	
Peak Force (N)	3030.66	549.12	0.989		2441.14	451.51	0.987		<0.001	0.788	
			0.986	0.992			0.982	0.990		0.583	0.990
Relative Peak Force (N/bw)	3.81	0.54	0.983		3.47	0.48	0.977		<0.001	0.448	
			0.978	0.988			0.969	0.983		0.258	0.636

Key: IMTP, isometric mid-thigh pull; AVG, average; DIS, distribution; ICC, intraclass correlation coefficient; dark green cell shading, excellent reliability; bright green cell shading, good reliability; ES, effect size; N, Newtons; bw, bodyweight.

Table 8.9. Isometric Mid-Thigh Pull Metrics Objective Benchmarks (Professional and Youth Soccer Players).

OBJECTIVE BENCHMARKS										
IMTP Metrics	**Group**	**Excellent**	**Very Good**	**Good**	**Above Avg.**	**Average (Avg.)**	**Below Avg.**	**Poor**	**Very Poor**	**Extremely Poor**
Peak Force (N)	1st Team	**4678**	**4129**	**3580**	**3305**	**3031**	**2756**	**2482**	**1932**	**1383**
	Youth Team	**3796**	**3344**	**2893**	**2667**	**2441**	**2215**	**1990**	**1538**	**1087**
Relative Peak Force (N/bw)	1st Team	**5.4**	**4.9**	**4.4**	**4.1**	**3.8**	**3.5**	**3.3**	**2.7**	**2.2**
	Youth Team	**4.9**	**4.4**	**3.9**	**3.7**	**3.5**	**3.2**	**3.0**	**2.5**	**2.0**

Key: IMTP, isometric mid-thigh pull; N, Newtons; bw, bodyweight.

8.4 DISCUSSION

Objective benchmarks (i.e., goal setting) cannot be prescribed for key tests and metrics without the existence of cohort-specific normative data sets [114], and published normative data and benchmarks should only be used within comparable groups [30]. To the authors' knowledge, this study is the first to produce normative data and objective benchmarks for key CMJ, CMRJ, and IMTP metrics in professional and youth soccer players and investigate age-specific differences between groups with an appropriate sample size. The main findings of this study were all metrics demonstrated good to excellent rank-order reliability, which is crucial when compiling normative data [114], and the majority of CMJ (25/32), CMRJ (24/30), and all (2/2) IMTP metrics discriminated between professional and youth soccer players in the EFL League 2. The original hypothesis was accepted for the CMJ test, where significant differences were identified in all outcome (4/4), propulsive kinetic (6/6), and relative propulsive kinetic (4/4) measures, but trivial insignificant differences were identified in all strategy (4/4) measures. The same pattern was observed for the CMRJ test, with the exception that significant differences were identified in less relative propulsive kinetic (1/4) measures (i.e., only in relative mean propulsive power) in the RJ portion, despite all propulsive kinetic (4/4) measures demonstrating moderate to large differences between groups, and a moderate difference in braking depth was identified between groups. As was hypothesised, professional soccer players demonstrated moderately greater absolute peak force in the IMTP than youth soccer players. Contrary to the hypothesis that no difference in relative peak force would be observed between groups, which was based on previous findings of similar research in youth male [39] and female [38] soccer players, significant yet small differences in relative peak force were also observed between groups, representing a progressive increase with age.

Moderate differences in body weight were identified between professional and youth soccer players for both the CMJ and CMRJ tests. Professional soccer players were 93.6 N (9.6 kg) heavier than their youth counterparts. This is a noteworthy finding because, in soccer, success in physical competition is driven by players' capacity to effectively accelerate their own body weight [296]. Although an increased body weight may be a natural process in maturation from adolescence through adulthood, and can be an advantage in physical duels in soccer (e.g., whilst jostling for positional space), this means that professional players need to produce greater net propulsive impulse than youth players to achieve an equal TOV and, therefore, JH in VJ tasks [112], and acceleration and deceleration of their body during on-field actions [100]. Therefore, the authors propose that the continuous monitoring of changes in soccer players' body weight should be considered when comparing between groups or monitoring individuals over time, which will permit appropriate ratio scaling of relevant data. Jump momentum has been proposed as an important measure in collision sports (e.g., rugby league) [288], due to its strong associations with sprint momentum (r = 0.78–92), and a highlighted importance of sprint momentum (i.e., for tackling) over sprint velocity in such sports [322]. Large differences in net propulsive impulse (which is equivalent to jump momentum) between professional and youth (U19) male rugby league players from an English Championship club have been reported [27]. Similarly, jump momentum discriminated between professional and youth soccer players in this study, where it was significantly and largely greater for professional soccer players in the CMJ test and both portions of the CMRJ test. Thus, these results indicate a significantly and largely greater net propulsive impulse generated in these VJ tests for professional over youth soccer players [15]. In soccer, sprint velocity is also an important factor for performance [288], as the displacement of the COM achieved when accelerating (e.g., when aiming to reach the ball first) depends on the velocity with which one leaves the ground (i.e., TOV) [288]. In this study, professional soccer players produced significantly greater JH than youth soccer players in both the CMJ test (moderate ES) and the RJ portion of the CMRJ test (small ES). Previous research has also reported small to large (Hedge's g = 0.41 to 1.05) increases in CMJ JH from the U10 through the U12, U14, and U16 youth age groups in female soccer players [38]. However, no comparable values for female youth (U18) vs professional soccer players are available in literature.

Despite the abovementioned considerations for the continuous monitoring of changes in soccer players' body weight, highlighting and reporting it within a squad can be a sensitive and uncomfortable issue for players and coaches. Jump momentum can overcome this issue when integrated into the evaluation process alongside JH, where JH is representative of TOV (i.e., calculated as TOV^2 divided by 19.62) [230] and jump momentum is equated as TOV multiplied by mass [288]. For example, a maintenance in JH but an increase in jump momentum over time would discretely highlight an increase in body mass. This would also indicate an increase in net propulsive impulse production as it is equal to jump momentum (as per the impulse-momentum theorem), and because TOV is equivalent to relative propulsive impulse production. Thus, maintaining TOV with an increase in mass would require greater net propulsive impulse production. Therefore, it seems rational to state that objective benchmarks may be created utilising JH and jump momentum for soccer players as when utilised together they provide key information regarding the interaction between the TOV and weight of the COM. Additionally, as both metrics also discriminated between professional and youth players in the CMJ and CMRJ tests, a focus on developing these attributes would aid youth soccer players' progression towards to professional standard.

Strategy metrics did not differentiate between professional and youth soccer players for the CMJ test. Given that net propulsive impulse production is equal to the net propulsive force multiplied by the propulsive phase time, this means that all differences in jump momentum between groups were caused by an increase in kinetic output (i.e., net propulsive force production) through the same strategy (i.e., over the same propulsive phase time), in the CMJ test. A single strategy metric (i.e., braking depth) demonstrated significant moderate differences between groups in the RJ portion of the CMRJ test, with professional soccer players (0.11 m) braking deeper than youth soccer players (0.09 m) by 2 cm. These braking depths are very shallow in comparison to the deeper countermovement depths seen in the CMJ test (0.28 m for both groups), yet the youth soccer players were braking around ~18% shallower compared to professional soccer players. However, this difference in braking depth could partly be due to professional soccer players being 3.37% taller on average (184 ± 7 cm) than their youth counterparts (178 ± 17 cm), and given the net braking impulse (i.e., landing momentum) during the RJ portion was meaningfully greater by 20.84% for professional (219.06 ± 27.88 N.s) over youth (177.71 ± 24.71 N.s) soccer players. This increased landing momentum was caused by professional soccer players recording significantly and moderately greater body mass and JH in the CMJ portion (and thus fall height in the RJ portion) [21, 171]. Like the CMJ test, the CMJ portion showed no difference in time to take-off between groups, so these differences in CMJ portion JH (i.e., RJ portion fall height) are entirely due to superior kinetic output. Therefore, it is potentially more impressive that the professional players produced a superior CMJ portion JH, despite having a greater body weight, and then handled a greater subsequent landing momentum in the RJ portion by producing greater net braking impulse, with greater braking depth, but with no difference in GCT.

Kinetic measures provide an objective overview of how the outcome of a VJ task is produced. As described, measures such as mean and peak propulsive force can help to explain changes in net propulsive impulse. Interestingly, mean and peak propulsive force demonstrated large and moderate significant differences between professional and youth soccer players for the CMJ test and RJ portion of the CMRJ test, respectively. When comparing kinetic output within and between groups, relative kinetic measures might provide a fairer comparison as the differences in absolute values between professional and youth soccer players will have been influenced by the different in body weight between groups. Small to moderate significant differences were identified between groups for all relative kinetic metrics in the CMJ test, however, only relative mean propulsive power demonstrated differences in the RJ portion of the CMRJ test. Despite the applicability for use in the CMJ test, relative kinetic metrics do not hold the same utility as objective benchmarks in the CMRJ test, where all CMJ relative kinetic metrics reported in this study can be considered for use, but only relative mean propulsive power for the RJ portion of the CMRJ test. Additionally, it is still important to understand the constituent parts of a relative measure as to understand whether a difference is due to a change in kinetic output, body weight, or a combination of both. Therefore, a combination of kinetic and relative kinetic measures can be proposed as options to utilise for objective benchmarks and focuses for physical development alongside those which illustrate the outcome (i.e., JH).

Despite strategy variables demonstrating minimal differences between groups for VJ tests, practitioners may still require an idea of the strategy employed to achieve the outcome. Ratio metrics have been recommended for VJ tasks in previous research discussing metric selection for monitoring changes in NMF [115], as they provide information regarding the outcome (e.g., JH) and the way it was achieved (e.g., GCT). Time-relative ratio metrics such as the RSI, mRSI, and FT:CT have been proposed to possess utility for this purpose [323, 324]. Despite these measures having gained much traction in sports performance research in recent years [59-61, 66, 67, 113, 165, 168, 169, 175, 183, 221, 229, 266, 316, 323-331], this study is the first to provide objective benchmarks for ratio metrics in the CMJ and CMRJ tests in professional and youth soccer players utilising an appropriate sample size. Professional soccer players demonstrated significantly greater ratio values (small ES) for both the CMJ (mRSI and FT:CT) and RJ portion of the CMRJ (RSI and FT:CT) tests. These findings are similar to research by McMahon et al. [27], who identified CMJ time to take-off was similar between groups, but professional players jumped higher (large ES = 0.91), which led to them achieving a higher mRSI (moderate ES = 0.58). Because CMJ-derived mRSI and FT:CT and RJ portion-derived RSI and FT:CT discriminate between groups, these measures can be proposed as objective benchmarks in soccer players.

Adding to the findings of previous research which identified significant increases in IMTP-derived peak force between each consecutive age category (U12 through U18) in youth male soccer players of English professional football clubs [39], this study reports a significant and moderate difference between youth (U18) and professional male soccer players of English professional football clubs. The average peak and relative peak force for the youth (U18) sample presented in this study (2441 ± 452 N and 3.5 ± 0.5 N per body weight, respectively) can be considered representative as it compares similarly to the values of youth (U18) male soccer players (2267 N [± SD not reported] and 3.2 N per body weight [± SD not reported], respectively) in the study by Morris et al. [39]. The peak force values presented in this study and by Morris et al. [39] would be considered "very poor" in relation to the objective benchmarks of the professional soccer players produced in this study. For comparison, the relative peak force values presented in this study would be considered "below average", and those presented in the study by Morris [39] would be considered "very poor", in relation to the objective benchmarks of the professional soccer players produced in this study. Contrary to results by Morris [39] and Emmonds [37, 38], who identified minimal differences in IMTP-derived relative peak force between youth age groups in male and female soccer players, the results of this study show that professional soccer players demonstrated significantly greater relative peak force than their youth counterparts, albeit small in magnitude.

A key process of neuromuscular development is a focus on maximal force expression (i.e., maximum strength), and then a focus on the ability to apply high GRFs under progressively constrained movement times in tasks specific to the athlete's sport [332]. High and positive correlations between CMJ-derived peak power and IMTP-derived peak force ($r = 0.77$ to 0.94) have been reported previously [333-336], so the greater physicality demonstrated by professional over youth soccer players in VJ tasks in this study is likely related to greater maximal and relative strength values demonstrated in the IMTP test. When male youth soccer players in EFL clubs reach the "YT" level, they enter a full-time schedule and access to consistent S&C provision. Contrary to this, youth soccer players from the U12 to U16 (i.e., "youth development") phase typically perform a two-hour training session twice per week and get limited access to S&C provision. The differences in findings of this study compared to previous [37-39] could reflect a lack of strength development at EFL male and female youth academies throughout the YDP compared to the full-time YT and professional phases.

Following the 2020-2021 season, the best European domestic football competitions over the previous five seasons were considered by UEFA to be the EPL, German Bundesliga, Spanish Primera División (i.e., La Liga), and Italian Serie A [337]. England has more association football clubs (over 40,000) than any other country, with a total of 92 professional football clubs competing across the top four professional leagues of the English football pyramid, consisting of the EPL (20 teams) and the EFL Championship, League 1, and League 2 (24 teams each). For comparison, a total of 56, 42, and 40 professional football clubs compete across the top three professional German football leagues (Bundesliga, 2. Bundesliga, and 3. Liga), top two professional Spanish football leagues (Primera División and Segunda División), and top two professional Italian football leagues (Serie A and Serie B), respectively. English football is traditionally characterised by a more direct and fast style of attacking play with

constant physical defending with strong tackles [337]. This style of play compares more similarly to the German Bundesliga than any other European football league, where teams possess a constant and fast speed of play, whilst the Italian Serie A is known for teams with high tactical competency in defence and a well-developed use of the counter-attack [337].
The authors of the first study to utilise artificial intelligence to directly compare how teams in these four European football leagues technically and tactically relate to one another suggested that the higher-ranked teams in the EPL during the 2018/2019 season adopted a style of play more similar to that seen within the Spanish Primera División (i.e., La Liga), which is characterised by high ball possession and excellence in individual technical skills, which was considered a result of frequent involvement in European competitions [337]. The authors concluded that an understanding of these distinct characteristics of play could be the key to success in domestic and European competitions, where different technical and tactical metrics might be better suited as performance indicators depending on the specific European league [337]. The physical testing data presented in this study was collated utilising professional and youth soccer players from the EFL League 2, and to the author's knowledge, a direct comparison of physical capacity across competitive European football leagues has not yet been performed. Thus, similar to the comparisons of technical and tactical capabilities made by García-Aliaga et al. [337], future research should explore the opportunity to compare physical capacity via force-plate derived force-time characteristics in professional and youth soccer players across Europe's best professional football leagues.

8.5 CONCLUSION

Given the number of discriminations in physical measures between professional and youth (U18) soccer players in EFL clubs, physical development is seemingly critical for youth soccer players as they progress towards the professional level. Despite weighing 93.6 N (9.6 kg) more, professional soccer players produced a significantly greater outcome in VJ tasks, owing to significantly greater kinetic (i.e., net propulsive impulse [equal to jump momentum], peak and mean force and power, and relative peak and mean force and power) output, but with equivalent strategy. Due to this, professional soccer players also recorded significantly greater ratio metric values (e.g., mRSI and RSI), representing greater reactive strength capacity. Professional soccer players displayed significantly greater absolute and relative isometric strength of over their youth counterparts, an area where youth were considered "very poor" and "below average", respectively, based on the objective benchmarks of the professional soccer players. Based on the information reported in this study, for the CMJ test and RJ portion of the CMRJ test, the authors propose that soccer players may utilise objective benchmarks for JH as the elected mass relative outcome measure and jump momentum as the elected mass inclusive outcome measure, as the combination of these two metrics can inform of the interaction between TOV and body weight, and discretely inform of differences in body weight where highlighting and reporting it within a squad might be a sensitive issue. Additionally, two relative kinetic measures such as relative mean propulsive force (impulse-momentum theorem metric) and power (work-energy theorem metric) would help to explain differences in the outcome, and kinetic measures alone (e.g., mean propulsive force and power) would provide additional context as to whether a difference in a relative measure was due to differences in kinetic output, body weight, or a combination of both. Finally, a ratio metric (e.g., mRSI or RSI) would provide an additional layer of context regarding the strategy performed relative to the outcome (i.e., reactive strength capacity). For the IMTP test, soccer players may utilise objective benchmarks for peak force and relative peak force. Professional and youth soccer players in the EFL League 2 can utilise these measures to gauge their players' physical capacity relative to the league they compete in, and where they aim to be (i.e., youth progressing to the professional level). The authors suggest that EFL clubs should prioritise providing consistent strength and power training to "YT" soccer players within their S&C programming to improve these areas.

EXPERIMENTAL STUDY 4

9 MONITORING ACUTE CHANGES IN COUNTERMOVEMENT JUMP NEUROMUSCULAR FUNCTION IN SOCCER ATHLETES

9.1 INTRODUCTION

In professional soccer, player availability is directly associated with team success, where the teams experiencing fewer injuries typically outperform those who experience more injuries throughout the course of a competitive season [285]. Physical adaptations in response to exercise occur only during rest, yet soccer players are required to compete repeatedly with minimal recovery time (e.g., 48 to 72 hours later) due to congested fixture schedules [72, 74, 110]. Following a sufficient physical stimulus, an improper recovery (e.g., as a result of match frequency) may result in residual fatigue [107] and an athlete might not reach the supercompensation phase [77, 78]. Acute negative alterations in physical preparedness are likely to immediately effect on-field physical output and increase the potential for non-contact injuries [72, 74]. Chronically, this would also lead to sub-optimal developments in physical preparedness and increase the risk of reduced performance, non-functional overreaching, injury, and illness [338]. This is an issue particularly because stronger players (e.g., who produced greater lower body force in the half-squat exercise) have demonstrated less muscle damage (measured via levels of CK) at 48 h post-match [339]. As per the fitness-fatigue paradigm, the optimisation of physical preparedness can be achieved through enhancements in physical fitness and the mitigation and recovery from physical fatigue [77]. However, the degree to which each individual athlete’s body responds (i.e., internal response) to a physical training stimulus (i.e., external workload) is idiosyncratic [19]. Additionally, high-intensity external workload differs between competing athletes, therefore, levels of neuromuscular fatigue and preparedness will differ between soccer athletes following training and competitive matches [120]. Subsequently, accurately managing individual physical preparedness is desirable in professional soccer to reduce the risk of non-contact injury and optimise physical output [72, 74]. Objective measures can help in identifying the magnitude of fatigue an athlete has incurred which would help practitioners prescribe systematic strategies and time periods to optimise recovery [338].

Objective measures provide the most effective means of monitoring the magnitude and time course of changes in physical preparedness resulting from physical activity [129]. Objective information is used by physical performance coaches to appropriately plan training for recovery back to and beyond baseline, to ensure it is optimised for when it is required most (i.e., for competition). Accordingly, there is a growing emphasis within sports science literature on innovative strategies to evaluate acute changes in physical preparedness, with a plethora of biochemical, biomechanical, and physiological markers available that help to inform coaching staff about an athlete's state of fitness, fatigue, and projected recovery [23, 110, 130]. For example, force plates are now among the most frequently used biomechanical apparatus in the field of sports science where coaches regularly evaluate their athletes' NMF via a range of tests (e.g., ballistic and plyometric VJ tests) [22]. Force plates were used by approximately 50% and 30% of surveyed S&C coaches working in professional soccer [161] and professional cricket [160], respectively. The rise in use of force plates amongst S&C coaches is likely due to the availability of more affordable force plate systems, some of which have been validated against industry gold standard systems [57, 114, 163]. Recent developments in force plate systems facilitate an opportunity to gain informative data on NMF in practical settings due to their accuracy, robustness, practicality, and thus feasibility [25, 111]. These factors are important to consider given that the monitoring of NMF and determining changes in physical preparedness is a task specific to, and historically a luxury only available to, elite sports organisations. Thus, it makes sense that most literature related to the topic is performed with populations defined as elite or professional athletes, with fewer investigations in collegiate, university, and youth athletes [23].

Researchers have identified different approaches regarding force plate test and metric selection [23]. This is evidenced in a scoping review of practices of evaluating changes in physical preparedness which has been performed in with regards to changes pre- to post training interventions (e.g., > 1 month) [23]. However, there is a lack of research summarising how best to utilise force plates to monitor acute changes in lower-body NMF, where many studies have been conducted with vastly different data collection and analysis procedures [43-49, 52-56, 65, 98, 116, 233, 239-244]. Within chapter 4, the aim of the scoping review was to identify, map, and describe which practices exist in the context of monitoring acute (<1 week pre- to post-physical stimulus) changes in NMF using force plates. The results of the review illustrated the similarities, differences, and gaps in the body of evidence retrieved regarding the specific force plate data collection and intervention procedures employed. The conclusions presented in the scoping review (Chapter 4) indicated that major methodological differences were present across all studies, such as in subject demographics (e.g., sports assessed), data collection protocols (e.g., test selection), study design (e.g., testing timepoints), and a general lack of reporting and uniformity in metric definitions, metric calculations, and phase terminology across studies. This means that an accurate comparison of results across studies (e.g., via meta-analysis) was not possible, and generalized conclusions about the application of specific tests and metrics for monitoring acute changes in NMF using force plates would be premature. It was recommended in the review that research needs to be employed with appropriate and standardised study designs across various sports populations, to determine metrics' sensitivity to change in real-world environments where the information will be applied. For example, in team-sports (e.g., soccer) applied around competitive matches (e.g., within 15 minutes pre- and post- an in-season competitive match), whilst reporting context of TL determination, if the intended data is to inform recovery processes. The suggestions for future research provided in the scoping review have contributed towards forming the rationale and the data collection protocols of the current study on monitoring acute changes in NMF using force plates.

The CMJ test is the most popular test used to assess longitudinal developments in NMF in the football codes [23]. It is employed as a measure of ballistic "slow" SSC capacity [165], with the results of the scoping review (Chapter 4) also highlighting that the CMJ was the most popular test used to assess acute changes in NMF, with JH identified as the most popular CMJ metric. The results of the reliability "study c" (Chapter 7 Section 7.10) identified the CMJ produced more than 3 times the number of reliable metrics (N = 19 out of 33) than the RJ portion of the CMRJ test (N = 5 out of 27) in a test-retest reliability design with youth soccer players in the in-season period. Within the reliability study, JH demonstrated good absolute and relative reliability based on the CV and ICC 95% CIs. Utilising the CMJ test, Thorlund et al. [52] identified a significant ($p < 0.01$) reduction of 5.2% in JH from immediately pre- (~0 min) to immediately post- (~0 min) simulated handball match, in "elite" male handball players. Similarly, Gathercole et al. [65] identified a reduction in JH with a small ES (0.34) immediately post- (~0 min) a high-intensity intermittent-exercise running test, in college level male team sport athletes. Contrary to these findings, Scanlan et al. [239] found no statistical difference in JH immediately post- (~2 min) a Basketball Exercise Simulation Test, in Junior Level Male Basketball players, and Boullosa et al. [44] found an increase in JH from immediately post- (~2 min) a Université de Montréal track test, in mixed level male and female endurance athletes.

There is seemingly a lack of uniformity in findings across studies [44, 52, 65, 239] which indicates that the outcome of a CMJ test might not necessarily be hindered following intense physical activity, and thus, JH might not be the best indicator of acute changes in NMF. Spencer et al. [42] concluded with similar assumptions when assessing full-time professional English National League soccer players, where no significant difference in JH from pre- (-90 min) to post- (+15 min) competitive soccer match was reported, but significant ($p < 0.05$) reductions in body mass, jump momentum, and countermovement depth were seen. A maintenance of JH when body mass has decreased indicates a negative change in kinetic output, specifically, less net propulsive impulse (which is equal to jump momentum) has been produced overall. Therefore, it may be prudent for practitioners to consider a combination of categories such as ratio (e.g., RSI, mRSI), strategy (e.g., GCT, time-to take-off, countermovement depth), and kinetic (e.g., mean and peak propulsive force and power) metrics for acute monitoring, rather than assessing the outcome (e.g., JH) alone [186], to provide a better representation of changes in NMF over time [27, 28, 67, 113, 118, 162, 178, 185]. As practitioners often have limited time, staffing, and facilities, a minimal approach of selecting metrics which hold utility for monitoring acute changes in NMF as a proxy for determining neuromuscular fatigue is essential. To achieve this, further assessment is required to determine the applicability of CMJ metrics (e.g., outcome, strategy, kinetic, and ratio) for monitoring acute changes in NMF.

When monitoring acute changes in NMF, it is difficult to isolate a "real" change in value due to the existence of inherent variability, caused by biological variability and measurement error [50, 202]. When conducting physical performance tests on a frequent basis (e.g., daily or weekly "fatigue" monitoring) to immediately inform training direction, simply observing a raw value increasing or decreasing via central tendency statistics (e.g., mean, median, or mode) is not the recommended approach to determining difference [41]. The utilisation of p-value-based analyses of difference (e.g., t-tests) is prevalent in studies aimed at detecting statistically significant group-level acute changes in NMF for specific metrics, across various sports [42-49]. However, such statistical methods do not inform as to a "real" modification in performance by considering the reported change in relation to random measurement error [50]. Measurement error can be estimated via methods such as the SEM, which is derived from the SD of the within-group between-session differences in test-retest reliability designs [50]. By estimating the 95% CIs of the SEM, the MDC can be established in unit of measurement and percentage format and applied on a group level [50]. With this statistical approach, one can deduce the minimum percentage change required for an individual's score to change for it to be considered a “real” change, that is, a performance change which is greater than the inherent measurement error [50]. Furlan et al. [50] reported significant changes in performance within a test-retest repeated measures study design, despite the changes being smaller than the established MDC, concluding that the results of the NHST incorporated changes mostly due to measurement error and not performance alone. The authors concluded by suggesting that NHST should be complimented with statistics such as SEM and MDC to inform as to the likely cause (i.e., within or beyond measurement error) of reported changes in performance. However, a lack of utilisation of such approaches is seen within research focussed on monitoring acute changes in NMF [42, 52-56], which must be addressed.

9.1.1 Aims

The aim of this study was to determine the effectiveness of evaluating CMJ performance via force plates for monitoring acute changes in lower-body NMF due to in-season competitive match-play, in youth soccer athletes. The primary outcome of this research is to provide researchers and practitioners with examples of CMJ metrics that have and have not demonstrated statistical and meaningful change immediately (+15 mins) and +48h (Match Day [MD] +2) following a competitive match. This will be indicated by NHST and ESs as performed in similar research [44, 52, 65, 239], and the inclusion of detecting meaningful difference via the MDC (values established in Chapter 7 Test-Retest Reliability). A secondary outcome of this research is to provide researchers and practitioners with information regarding the relationships between individual changes in CMJ metrics and external workloads (e.g., total duration, total distance, average speed, maximum speed, HSR distance, sprint distance, number of HSR, number of sprints, and number of decelerations) performed during in-season competitive match-pay, in youth soccer athletes. This information can then be directly implemented into practice when choosing relevant metrics for the purpose of monitoring acute change in NMF in response to in-season competitive match-play, in youth soccer players. It was hypothesised that a reduction in body weight will be seen from pre- to immediately post-match, in this study, as might be expected due to fluid loss via perspiration [108]. It was also hypothesised that reductions in kinetic measures such as mean propulsive force and jump momentum (equal to net propulsive impulse) would be seen from pre- to immediately post-match. However, a reduction in both aspects means that mass relative outcome measures such as TOV (equal to relative propulsive impulse) and JH might be unchanged, similar to results of previous research [42].

9.2 METHODS

9.2.1 Study Design

A within subjects, observational, cross-sectional, repeated measures study design was used to determine effects of match play on CMJ performance. As per the most common testing timepoints based on the results of the *scoping review* (Chapter 4), 3 testing occasions were prescribed per cohort: immediately pre-match (~15 mins), immediately post-match (~15 mins), and MD+2 (around ~48 hours post-match). This multiple time-point approach allowed for the identification of metrics which are sensitive to change, which can denote a reduction in NMF due to fatigue mechanisms from immediately pre- to post-match (e.g., due to metabolic stress and acidosis), due to fatigue mechanisms from immediately post-match to MD+2 (e.g., due to mechanical stress via muscle damage), and can plot the recovery of each athlete back to baseline from immediately pre-match to MD+2 (i.e., the next training day). Testing was not performed at ~24 hours post-match as this is the traditional day-off for EFL Youth Alliance League (U18) soccer players. All participants provided written informed consent or parental assent, as appropriate. Athletes were not permitted to be included in either study if they have experienced a lower limb injury within the 6-months prior to the scheduled testing. This study was pre-approved by the University of Salford institutional review board and conformed to the World Medical Association's Declaration of Helsinki 2013. As substitutions in competitive EFL Youth Alliance League (U18) soccer matches typically occur at 60 minutes (which allows all athletes to participate for either 60 or 30 minutes per match), athletes were permitted to be included in this study if they completed more than 60 minutes of their respective competitive match.

9.2.2 Participants

A trivial to small change in JH (ES = 0.03-0.47) reported across several studies [42, 65, 116] resulted in an average small change (ES = 0.28) in JH (i.e., the most commonly reported CMJ metric [23]) immediately following sports competition. An *a priori* sample size estimation for a repeated measures, within factors, ANOVA was performed (G*Power, [22, 23]) which indicated that in 1 group consisting of 3 measurements, with an expected small ES (d = 0.28), an alpha set at 0.05, and expected correlation between measures is 0.75, the minimum sample size required to yield a statistical power of at least 0.95 was 18 subjects. A targeted sampling approach led to 3 professional EFL clubs being recruited for this study, from which athletes were employed as a soccer player on a full-time basis, in the EFL Youth Alliance League (U18) competitions, respectively, at the time of testing. The final sample for this study included 27

Youth Alliance League (U18) soccer players (age 16.9 ± 0.7 years; height 181.4 ± 5.4 cm; mass 73.6 ± 9.1 kg). Recruiting multiple clubs who compete in the Youth Alliance League enabled the pooling of results within this specific competitive level, which allowed for a more representative data set to be generated specific to this level of play, as opposed to if a single-club approach was utilised. Based on the participant classification framework produced by McKay et al. [31], these subjects would represent tier 3: highly trained (youth; EFL academy categories 3 to 4). All participants had previous experience performing the CMJ task on force plates in training and previous physical performance testing and were free from injury at testing (in-season).

9.2.3 Data Collection

Data collection took place during the first half of each club's 2023/2024 competitive season (i.e., in 2023). All testing was conducted "in-season", where the monitoring of NMF would usually occur within sports clubs during a regular competitive season. The CMJ test (slow SSC test) was utilised for the force plate testing. A standardised pre-match "RAMP" warm-up [340] was directed by each club's sports science staff who regularly deliver pre-match preparations on MD. The pre-match CMJ testing was performed immediately following the end of this warm-up. A familiarisation trial consisting of a submaximal effort CMJ was provided for each participant immediately prior to data collection. The post-match CMJ testing was performed immediately (within 15 minutes) following the completion of the match for every athlete, including those who were substituted off before the end of the match. Once these same players had reported back to training on MD+2 (+48 hours post-match), a brief (~10 min) gym-based warm-up consisting of ~5 minutes of low intensity stationary cycling, dynamic stretching, and a submaximal CMJ effort was directed by each club's sports science staff. The MD+2 CMJ testing was performed immediately following the end of this warm-up.

Participants performed three maximal effort CMJ trials with arms akimbo and were instructed to jump "as fast and high as possible" on each testing occasion. A full description of data collection procedures for the CMJ test can be found in Chapter 5 titled "General Methods". All GPS data was collected by the sports science practitioners at each club during each competitive match, from the commencement (i.e., from kick off or when the player was substituted into the game) until the point each individual player ended their contribution to the match (i.e., when they are substituted out or at the end of the match). The GPS units were positioned on the upper back between the scapulars by placing them inside fitted vests worn by the participants under their match shirts. Data was subsequently automatically analysed post-game via each system's cloud software. To ensure data accurately represented the players' contribution to the competitive match, the sport science practitioners created time-bands of (i.e., "clipping") match participation (i.e., when they started and ended their contribution to the match), and then downloaded the raw data files and provided them for this study. The GPS hardware and software used were determined by what was used at each respective club. Two separate clubs provided GPS data for a total of 18 players, where vest-based solutions were utilised to collect GPS data using a combination of Catapult Vector S7 (Catapult Group International Ltd, Melbourne, Australia) [341] and Fitogether Ohcoach (Fitogether Inc, Seoul, 04323, Republic of Korea) [342] systems, which measured position at 10 Hz.

9.2.4 Data Analysis

Data analysis was automatically performed after each trial via the HD Inc. proprietary software. A full description of the start of numerical integration and phase descriptions for the CMJ test (i.e., weighing, unweighting, braking, propulsion, and flight phases [260]) can be found in chapter 5 General Methods. A full description of the key variables extracted from the force-time records of the CMJ test can be found in Table 5.1. in chapter 5 General Methods section 5.2 Countermovement Jump. Data analysis was not performed on the GPS data by the researchers, but by sports science staff as part of their routine daily jobs. The authors had no control over the external workload performed during data collection, and information regarding external workloads was only provided post-match (i.e., there was no live information). Only the values of each variable for each athlete were be provided to the researchers for further use during the project. The variables provided included total duration (min), total distance (m), average speed (m/min), maximum speed (m/s), HSR distance (m), sprint distance (m), number of HSR (value), number of sprints (value), and number of decelerations (value). Sprint, HSR, and deceleration thresholds were set at >7.00 m/s, 5.5 to 7 m/s, and >3.0 m/s/s, respectively.

9.2.5 Statistical Analyses

All data was statistically analysed using a combination of Microsoft Excel (version 16; Microsoft Corp., Redmond, WA, USA) and Jamovi (version 2.4.14; Sydney, Australia) [343]. To allow for individual comparisons of change across testing timepoints, each individual's average across the three trials was calculated for every variable in each testing session. To allow for within-group comparisons of change across testing timepoints, the mean ± SD of all individual average values for each variable were equated for each testing session. Three comparisons were made across testing timepoints. The absolute change was calculated between immediately (-15 mins) pre- to immediately (+15 mins) post-match, immediately pre-match to return to training (+48 hours, MD+2), and immediately post-match to return to training. Absolute change was calculated as:

Session 2 Average – Session 1 Average

Where session 2 corresponds with the second testing session (e.g., +48 hours), and session 1 corresponds with the first testing session (e.g., post-match), in each comparison. The absolute change was then expressed as a %, calculated as:

(Mean Difference / Session 1 Average) * 100

To determine meaningful change in every metric, the percentage change in value was interpreted against the previously calculated MDC of each variable in *the reliability study of youth soccer athletes in the in-season period* (Chapter 7 Section 7.10) on a group and individual basis. To allow for group comparisons, the mean ± SD of the absolute and % differences between-sessions were equated for each variable. Based on the results of the *reliability study*, the chosen metrics of interest and corresponding determined MDC of each variable that were be utilised in the current study are reported in Table 9.2.

All data were normally distributed as indicated via the Shapiro-Wilks test in Jamovi before proceeding with the main statistical analyses (using an alpha level of 0.05). Then, repeated measures ANOVA, post-hoc analyses (corrected for familywise error rate with Tukey's honestly significant difference) of pairwise comparisons, and Hedge's *g* ESs (with 95% CIs) were utilised to assess changes between the three timepoints mentioned above. The ES were interpreted as trivial (≤0.19), small (0.20 to 0.49), moderate (0.50 to 0.79), or large (≥0.80) [214]. Pearson's correlation coefficients (corrected for familywise error rate with Bonferroni correction [344, 345]) were calculated for metrics which demonstrated significant differences ($p < 0.05$) in the pairwise comparison of pre-match (~15 mins) to immediately post-match (~15 mins; Table 9.3) and the 9 included GPS metrics (Table 9.4). Bonferroni correction was applied utilising the "single step" method by dividing the alpha level ($p < 0.05$) by the number comparisons being made [346, 347].

Table 9.1. Summary of Metrics and Minimal Detectable Change Statistics.

CMJ Metrics	**MDC**	**MDC %**
Body Weight (N)	9.69	1.37%
Peak Velocity (m/s)	0.11	4.10%
Takeoff Velocity (m/s)	0.11	4.28%
Jump Momentum (Kg*m/s)	8.26	4.43%
Flight Time (s)	0.03	4.75%
Mean Propulsive Velocity (m/s)	0.08	4.93%
Mean Propulsive Force (N)	121.33	7.43%
Peak Propulsive Power (W)	313.78	8.02%
Jump Height (m)	0.03	8.55%
Mean Propulsive Power (W)	220.45	9.38%
Propulsive Phase Time (s)	0.02	11.05%
Net Braking Impulse (N.s)	10.26	11.10%
Net Impulse Ratio (AU)	0.23	11.33%
Peak Propulsive Force (N)	268.17	12.76%
Countermovement Depth (m)	0.03	13.65%
Key: MDC, minimal detectable change.		

9.3 RESULTS

Descriptive statistics for force plate metrics are reported in Table 9.3. Descriptive statistics for GPS metrics are reported in Table 9.4. The repeated measures ANOVA demonstrated significant ($p < 0.05$) differences across testing timepoints for all metrics except peak propulsive force. Pairwise comparisons can be found in Table 9.3. From pre- to post-match, jump momentum, mean propulsive power, mean propulsive velocity, mean propulsive force, peak propulsive force, countermovement depth, net braking impulse, and body weight significantly reduced with trivial to moderate effect (Table 9.3). Net impulse ratio significantly increased with a moderate effect (Table 9.3). JH, FT, TOV, peak propulsive power, peak velocity, and propulsive phase time were not significantly or meaningfully (trivial) different pre to post match. (Table 9.3). From post-match to MD+2, JH, FT, TOV, net impulse ratio, peak propulsive power, peak velocity, and countermovement depth significantly reduced with small to moderate effect (Table 9.3). Countermovement depth, net braking impulse, and body weight significantly increased with trivial to small effect (Table 9.3). Jump momentum, mean propulsive power, mean propulsive velocity, mean propulsive force, and peak propulsive force were statistically unchanged with trivial effect (Table 9.3).

From pre-match to MD+2, JH, FT, jump momentum, TOV, mean propulsive power, peak propulsive power, mean propulsive velocity, peak velocity, and mean propulsive force significantly reduced with trivial to large effect (Table 9.3). Propulsive phase time and body weight significantly increased with trivial to small effect (Table 9.3). Net impulse ratio, peak propulsive force, countermovement depth, and net braking impulse were statistically unchanged with trivial effect (Table 9.3). A variety of meaningful increases and decreases relative to the MDC were identified for every metric on an individual level (see Appendix 12.5). Every metric demonstrated meaningful change for an individual from pre- to post-match, and post-match to MD+2 (see Appendix 12.5). Propulsive phase time and peak propulsive force did not demonstrate meaningful change for any individual from pre-match to MD+2 (see Appendix 12.5). The nine CMJ metrics which demonstrated significant ($p < 0.05$) change from pre- to post-match were taken forward with the nine GPS metrics for the Pearson's correlations. The "single step" method of Bonferroni correction was applied by dividing the alpha level ($p < 0.05$) by 81 (i.e., the number comparisons being made) [346], and resultantly, a corrected alpha level of 0.006 was utilised to determine significance. Following this determination, a significant relationship was not identified between any force plate and GPS metric.

Table 9.2. Descriptive Statistics and Comparisons Between Time-Points.

CMJ Metrics	Pre-Match	Post-Match	MD+2	Pre-Match vs Post-Match				Post-Match vs MD+2				Pre-Match vs MD+2			
	Mean ± SD	Mean ± SD	Mean ± SD	P Value	ES	-95	+95	P Value	ES	-95	+95	P Value	ES	-95	+95
Jump Height (m)	0.37 ± 0.04	0.37 ± 0.04	0.36 ± 0.04	0.853	-0.02	-0.31	0.22	0.003	-0.37	-0.58	-0.12	< .001	-0.39	-0.64	-0.20
Flight Time (s)	0.56 ± 0.04	0.55 ± 0.04	0.54 ± 0.04	0.593	-0.07	-0.33	0.16	0.023	-0.26	-0.46	-0.02	0.004	-0.31	-0.56	-0.12
Jump Momentum (Kg*m/s)	199.53 ± 30.44	195.72 ± 28.68	195.65 ± 29.86	0.018	-0.13	-0.25	-0.03	0.96	0.00	-0.09	0.10	0.002	-0.13	-0.22	-0.05
Takeoff Velocity (m/s)	2.70 ± 0.16	2.70 ± 0.16	2.64 ± 0.17	0.801	-0.03	-0.34	0.21	0.004	-0.36	-0.56	-0.10	< .001	-0.39	-0.64	-0.19
Net Impulse Ratio (AU)	2.09 ± 0.26	2.24 ± 0.30	2.06 ± 0.30	< .001	0.52	0.26	0.83	< .001	-0.59	-0.90	-0.36	0.443	-0.11	-0.42	0.16
Mean Propulsive Power (W)	2363.75 ± 436.03	2260.48 ± 366.78	2239.29 ± 384.35	0.024	-0.25	-0.49	-0.07	0.559	-0.06	-0.22	0.18	< .001	-1.24	-1.81	-0.82
Peak Propulsive Power (W)	4112.36 ± 759.91	4169.42 ± 695.60	3957.12 ± 714.31	0.264	0.08	-0.07	0.22	< .001	-0.30	-0.43	-0.17	< .001	-1.55	-2.19	-0.95
Mean Propulsive Velocity (m/s)	1.64 ± 0.09	1.59 ± 0.10	1.60 ± 0.09	0.006	-0.57	-0.96	-0.23	0.703	0.07	-0.24	0.47	< .001	-0.52	-0.83	-0.26
Peak Velocity (m/s)	2.80 ± 0.15	2.80 ± 0.15	2.74 ± 0.16	0.872	-0.02	-0.32	0.22	0.003	-0.37	-0.58	-0.11	< .001	-0.39	-0.65	-0.19
Mean Propulsive Force (N)	1584.76 ± 244.37	1544.87 ± 214.38	1539.73 ± 225.28	0.029	-0.17	-0.34	-0.04	0.721	-0.02	-0.14	0.12	0.001	-0.19	-0.33	-0.10
Peak Propulsive Force (N)	1943.20 ± 307.36	1890.21 ± 292.23	1903.80 ± 318.79	0.049	-0.17	-0.36	-0.01	0.545	0.04	-0.08	0.21	0.068	-0.12	-0.29	-0.01
Propulsive Phase Time (s)	0.24 ± 0.03	0.24 ± 0.03	0.25 ± 0.04	0.463	0.08	-0.12	0.31	0.041	0.20	0.01	0.42	0.01	0.27	0.08	0.50
Countermovement Depth (m)	-0.29 ± 0.05	-0.28 ± 0.05	-0.30 ± 0.06	0.044	0.15	0.01	0.32	< .001	-0.24	-0.40	-0.12	0.28	-0.11	-0.32	0.09
Net Braking Impulse (N.s)	97.05 ± 16.40	89.59 ± 16.41	97.40 ± 18.80	< .001	-0.45	-0.67	-0.28	< .001	0.44	0.25	0.67	0.859	0.02	-0.17	0.29
Body Weight (N)	722.21 ± 89.27	710.87 ± 88.61	726.13 ± 91.10	< .001	-0.13	-0.16	-0.09	< .001	0.17	0.13	0.21	0.015	0.04	0.01	0.08

Key: m, metres; s, seconds; kg, kilograms; AU, arbitrary unit; W, Watts; N, Newtons; SD, standard deviation; ES, effect size.

Table 9.3. External Workload Performed During the Competitive Matches.

Name	Duration (min)	Total Distance (m)	Average Speed (m/min)	Max Speed (m/s)	HSR Distance (m)	Sprint Distance (m)	No. of HSR (times)	No. of Sprint (times)	No. of Decel. (times)
Mean	81.15	9299.21	107.61	7.49	476.68	94.41	46.85	10.77	22.29
SD	20.74	2518.48	28.26	1.93	253.05	71.22	21.91	6.26	9.16

Key: SD, standard deviation; HSR, high speed run; min, minutes; m, metres; s, second; No., number; Decel., decelerations.

9.4 DISCUSSION

The purpose of this study was to determine CMJ metrics which can be proposed for monitoring acute changes in lower-body NMF due to in-season competitive match-play in youth soccer players, after demonstrating statistical and meaningful change immediately (+15 mins) and +48h (MD+2) following a competitive match. It was hypothesised that, from pre- to immediately post-match, a reduction in body weight would be seen, reductions in kinetic measures such as mean propulsive force and jump momentum (equal to net propulsive impulse) would be seen, and a reduction in both aspects means that mass relative outcome measures such as TOV (equal to relative propulsive impulse) and thus JH might be unchanged, similar to results of previous research [42]. These hypotheses are accepted as from pre- to immediately post-match a statistically significant ($p < 0.001$) and meaningful (1.57%) reduction in body weight of 11.34 ± 5.17 N was seen, significant reductions in mean propulsive force, mean propulsive velocity, mean propulsive power, and jump momentum [equal to net propulsive impulse] were seen, and resultantly, TOV, FT, and JH were unchanged (Table 9.3).

On an individual basis, body weight reduced for every participant from pre- to immediately post-match and was the metric with the greatest number of participants (N = 15 out of 27) whose increase exceeded the MDC (range of 1.64-3.48%) across these testing timepoints, where the remaining 12 participants' reduction was within the MDC (range of 0.29-1.36%). This study's findings coincide with those of Spencer et al. [42], who were the first authors to evaluate acute changes in body mass and their relation to key outcome measures (i.e., JH) immediately following a competitive soccer match (+15 mins) in professional soccer players, where a statistically significant ($p < 0.001$) reduction of 2% in body mass post-match (+15 mins) with large effect (ES = 1.66) was identified. To the author's knowledge, the current study is the first to evaluate acute changes in body mass and their relation to key outcome measures (i.e., JH) from immediately pre- (+15 mins) to immediately post- (+15 mins), and at +48 hours (MD+2), following a competitive soccer match in youth soccer players, therefore, the results of this study add to those of Spencer et al. [42] in confirming that body weight reduces immediately following a competitive soccer match in youth and professional soccer players.

From immediately (+15 mins) post-match to MD+2, a statistically significant ($p < 0.001$) increase in body weight of 15.27 ± 7.16 N (2.15%) was seen in youth soccer players, indicating a recovery of the potential fluid loss via rehydration [108]. On an individual basis, body weight increased for almost all (except one with a 0.43% decrease) participants from post-match to

MD+2 and was the metric with the greatest number of participants (N = 21 out of 27) whose increase exceeded the MDC (range of 1.63-4.28%) across these testing timepoints (see Appendix 12.5). The sole participant which had a reduced body weight across these timepoints also had a non-meaningful reduction in body weight (0.67%) from immediately pre- (+15 mins) to immediately post- (+15 mins), resulting in a non-meaningful reduction in body weight (1.09%) at MD+2 compared to pre-match, indicating a lack of change in body in response to competitive match-play in this participant (see Appendix 12.5). Regardless, the sample's average recovery in body weight was significantly (p = 0.015) greater by 3.92 ± 7.84 N (0.54%) at MD+2 compared to pre-match, where almost a third of participants (N = 7 out of 27) increase exceeded the MDC (range of 1.47-2.75%), and no meaningful reduction was identified, across these testing timepoints. To the author's knowledge, this study is first to report that body weight recovers back to and beyond baseline within 48 hours (i.e., from immediately post-match to MD+2) in youth soccer players, and in soccer players generally. This is a significant finding given that coaches aim for their players to return to training in as recovered a state as possible within this specific timeframe (i.e., EFL youth soccer players' competitive matches are on a Saturday, where Monday is their return to training). This also likely renders mass relative metrics as rather limited for the detection of acute changes in NMF, particularly over periods where changes in body weight are likely (i.e., a competitive match).

In addition to the statistically significant reductions in mean propulsive force (2.52%; ES = trivial), mean propulsive velocity (3.27%; ES = moderate), and mean propulsive power (4.37%; ES = small) seen from pre- to post-match, a meaningful reduction was identified on an individual basis by seven (7.51-13.39%), eight (5.52-17.68%), and eight (10.06-24.80%) youth soccer players for these measures, respectively, across these testing timepoints (see Appendix 12.5). These findings disagree with those of Oliver et al. [53], who found no statistical difference in mean propulsive force in youth soccer players (N = 10) from immediately (-0 mins) pre- to immediately (+0 mins) post- a 42- minute soccer-specific intermittent exercise test on a non-motorized treadmill, and those of Thorlund et al. [52] who found no statistical difference in mean propulsive force and power in male elite Danish National League handball players from immediately (-0 mins) pre- to immediately (+0 mins) post- a 50-minute simulated handball match. These discrepancies might be explained by the differences in intervention activity and external load performed, where the competitive match performed by participants in this study (81.15 ± 20.74 mins) elicited an average total distance covered of 9,299 m at an average speed of 107.61 m/min. Comparatively, the participants in the study by Oliver et al.

[53] covered an average total distance of 4,745 m at an average speed of 112.98 m/min, and in the study by Thorlund et al. [52] covered an average total distance of 6,527 m at an average speed of 130.54 m/min. Thus, despite the participants in the studies of Oliver et al. [53] and Thorlund et al. [52] working at a greater average speed, the lower average total distance covered of 4,554 m and 2,772 m, respectively, in comparison to the present study might explain the lack of reduction in kinetic output in those studies compared to this.

Despite the study by Spencer et al. [42] following similar protocols to the present study, specifically, testing pre- and post- a competitive soccer match which demonstrated similar external loads with a 81.15 ± 20.74 minute time played, and eliciting an average total distance covered of 9,550 m at an average speed of 98.90 m/min, the authors did not report any kinetic measures within their study so a comparison of findings of changes in kinetic output pre- and post- a competitive soccer match, as was done above for changes in body weight across these same testing timepoints, could not be made. Additionally, none of these studies included statistical methods beyond formal null significance hypotheses and magnitude-based testing (i.e., only used t-test and ES), so only group and not individual changes could be discerned (e.g., via the MDC used in this study). A future study following the protocols of Spencer et al. [42] with professional soccer players whilst including the kinetic measures utilised in the present study and MDC statistics may be performed to allow for a direct comparison of changes. No significant changes in mean propulsive force (0.33%; ES = trivial), mean propulsive velocity (0.41%; ES = trivial), and mean propulsive power (0.94%; ES = trivial), were seen from post-match to MD+2. Thus, all three measures were also significantly reduced (2.84-5.27%; ES = trivial to large) at MD+2 compared to pre-match.

Despite body weight recovering back to and beyond baseline during this period, kinetic measures did not, in youth soccer players. This would suggest that body weight recovers more quickly than NMF following a competitive soccer match in youth soccer players. To the author's knowledge, this study is first to report that kinetic measures do not recover back to baseline within 48 hours (i.e., from immediately post-match to MD+2) in youth soccer players. However, despite many individual reductions in these kinetic measures, only 3, 5, and 4 youth soccer players demonstrated *meaningful* reductions in mean propulsive force (8.65-13.07%), mean propulsive velocity (4.93-7.57%), and mean propulsive power (10.59-16.44%), respectively, from pre-match to MD+2 (see Appendix 12.5), highlighting the need for an individualised recovery monitoring approach. Peak propulsive force demonstrated significant

(2.73%; ES = trivial) reductions from pre- to immediately (+15 mins) post-match and remained unchanged from post-match to MD+2. Consequently, peak propulsive force was statistically unchanged from pre-match to MD+2. Given this and the fact that the statistically significant changes were only trivial, this would explain why peak propulsive force was the only measure which did not demonstrate significant differences from the results of the ANOVA (Table 9.3).

Peak velocity followed an opposite trend, where no statistical changes were identified from pre- to immediately post-match, but significant ($p = 0.003$; ES = small; 2.13%) reductions were seen from immediately post-match to MD+2, resulting in it being equally significantly (2.20%; ES = small) less MD+2 compared to baseline. Because in the HD Inc. propriety software calculations the acceleration-time record is calculated by rearranging Newton's Second Law of Motion, by dividing the net force-time record by the athlete's body mass (acceleration = net vertical GRF / body mass), and velocity based measures are calculated by numerically integrating the acceleration-time record with respect to time using the trapezoid rule, this pattern is likely due to the reductions in propulsive force being concurrent with the reductions in body weight from pre- to immediately post-match. However, whilst propulsive force remained reduced from immediately post-match to MD+2 but body weight recovered during this period, propulsive velocity resultantly reduced. As power is a combination of force multiplied by velocity (traditionally calculated as work divided by time via work-energy theorem), peak propulsive power remained unchanged from pre- to immediately post-match, but significantly (5.09%; ES = small) reduced from immediately post-match to MD+2, resulting in it being significantly (3.77%; ES = large) less at MD+2 compared to baseline. A limitation to peak kinetic values is that changes in strategy alter force-time characteristics, where a more shallow and "stiffer" strategy elicits greater peak forces over less time resulting in a reduced net propulsive impulse [184]. Thus, an alteration in strategy (e.g., reduction in countermovement depth and propulsive phase time) because of neuromuscular fatigue would likely increase peak force and hide any potential reductions in NMF had the strategy remained the same. Additionally, peak values only represent the maximal value attained within a single frame (i.e., within 1 millisecond), and have no bearing on the outcome of a CMJ, which raises questions of their practical significance. Consequently, alongside the mixed results presented above, peak kinetic measures may be considered limited for monitoring acute changes in NMF over equivalent mean kinetic measures.

Propulsive phase time did not change from pre- to immediately (+15 min) post-match, but a significant (p = 0.041; ES = small) increase of 3.04% was observed between immediately post-match to MD+2, resulting in it being equally significantly (p = 0.01; ES = small) greater by 4.04% at MD+2 compared to baseline. Following the trend of changes in mean propulsive force and propulsive phase time, jump momentum (which is equal to net propulsive impulse, which is calculated as net propulsive force multiplied by propulsive phase time) was significantly (p = 0.018; ES = trivial) reduced by 1.91% from pre- to immediately (+15 mins) post-match, and saw no change from immediately post-match to MD+2, resulting in it being equally significantly (p = 0.002; ES = trivial) reduced by 1.94% at MD+2 compared to baseline. This finding agrees with that of Spencer et al. [42] who also reported significant (p = 0.049; ES = moderate) reductions in jump momentum from pre- to post- a competitive soccer match in professional soccer players. Thus, it seems that both mean propulsive force and net propulsive impulse (i.e., jump momentum) are significantly reduced following a competitive soccer match, and fail to recover fully within a +48-hour window in youth soccer players. From pre- to immediately post-match, a total of 7 players saw meaningful reductions in jump momentum which exceeded the MDC (4.67-12.55%), and only 2 of these saw a meaningful increase which exceeded the MDC (5.47-11.19%) back towards baseline (see Appendix 12.5). This again highlights the requirement for an individualised recovery monitoring approach, as the group data indicates a generalised group reduction, but these two specific athletes had recovered their jump momentum entirely during the 48 hours recovery period.

Jump momentum is equal to TOV multiplied by body mass, thus, a change in jump momentum relies on a trade-off of changes in body weight and TOV independently [288]. No changes were identified in TOV from pre- to immediately (+15 mins) post-match, therefore, the reductions in jump momentum during this period were due to the previously described reductions in body weight during this period. A maintenance in TOV with a reduction in body weight is a negative adaptation because propulsive impulse divided by body mass equals TOV [15], thus, achieving the same TOV with less body weight indicates less net propulsive impulse production was produced immediately post- relative to pre-match in youth soccer players [288]. This is safe to assume given that net propulsive impulse is equal to jump momentum, and a significant reduction in jump momentum was seen during this period. A significant (2.18%; ES = small) reduction was seen was identified in TOV from immediately post-match to MD+2, resulting in it being equally significantly (2.42%; ES = small) less at MD+2 in comparison to pre-match. This finding makes sense given that net propulsive impulse (i.e., jump momentum) remained reduced from immediately post-match to MD+2, whilst body weight returned to baseline during this period. Thus, as previously described, the full recovery of body weight with a lack of recovery of jump momentum (i.e., via a lowered mean propulsive force and maintained propulsive phase time) 48 hours after a competitive soccer match manifested as a reduction in outcome (i.e., TOV). Consequently, mass-relative outcome measures (e.g., TOV JH) may be rendered quite limited to explain changes in NMF immediately following a competitive soccer match where a change in body weight is likely and weight would therefore compromise the findings, and should therefore be utilised alongside other metric types (e.g., body weight, kinetic, and strategy metrics) to explain changes.

The author suggests that outcome measures may only be used for monitoring acute changes in NMF as secondary metrics whilst monitoring changes in the constituent parts (i.e., mean propulsive force, propulsive phase time, jump momentum [i.e., net propulsive impulse], and body weight) independently. These points support the results and conclusions of previous studies involving the pre- and post-match CMJ testing of male team sports athletes [42, 45, 52], where JH demonstrated a lack of change from immediately pre- to post-session. Because JH is calculated in this study as TOV^2 divided by 2 times g [230], any change in TOV is equivalent to a change in JH. Because FT is directly influenced by JH (practically but not equationally via forward dynamics), this explains why equivalent patterns of no change were identified from pre- to immediately (+15 mins) post-match in TOV, JH, and FT, but significant (1.69-4.28%; ES = small) reductions were seen from immediately post-match to MD+2. Consequently, these findings example that only one outcome measure is required when monitoring acute changes in NMF, if used at all. Spencer et al. [42] also attributed a lack of changes in outcome (i.e., JH) to reductions in body weight from pre- to post-session, concluding that JH may be insufficient to use alone to objectively monitor acute changes in NMF, despite the popularity of this metric [23] and commonality of this approach in professional soccer clubs.

To the author’s knowledge, this study is the first to determine the relationships between external load parameters (i.e., GPS metrics) from a competitive soccer match and acute changes in NMF (i.e., via force plate metrics) from immediately pre- (~15 mins) to immediately post- (~15 mins) the same competitive soccer match in youth soccer players. As nine force plate metrics demonstrated significant change across these testing timepoints, these were correlated with the nine GPS metrics included within this study to equal a total of 81 comparisons.

Following the application of a Bonferroni correction to produce an alpha level ($p < 0.006$), no relationship was determined between any GPS and force plate metrics in this study. Fraenkel et al. [348] defines correlation research as a form of descriptive research which describes an existing relationship between variables, and proposes a minimum acceptable sample size of no less than 30 subjects to provide an accurate estimate of the degree of a relationship. Despite this present study exceeding the established *a priori* sample size estimation for repeated measures ANOVA by 9 subjects, the GPS data was only provided for only two (N = 18) out of the three squads (N = 27) assessed for acute changes in NMF.

Based on the suggestions of Fraenkel et al. [348], a potential limitation to this result is the sample size, which may not have been large enough to find a significant relationship based on the number of correlations. Additionally, the external workload criterion set for eligibility to be included within this study was for an athlete to participate for a minimum duration of 60 minutes, as substitutions in competitive EFL Youth Alliance League (U18) soccer matches typically occur at 60 minutes (to allow all athletes to participate for either 60 or 30 minutes per match). This was a more appropriate criterion for the author to set given there was no control over a minimum external workload threshold during data collection, and information regarding external workloads was only provided post-match (i.e., there was no live information). However, factors relating to different tactical roles, playing positions, and opposition players will affect an individual's external workload within a squad resulting in players demonstrating different external workloads regardless within a similar duration [17]. Thus, an additional limitation to this study is that parameters for inclusion regarding external workloads could not be set. Future research could look to establish a relationship between acute changes in NMF via force plate metrics and GPS metrics taken with multiple teams throughout an entire competitive season to equate a more appropriate and larger sample, where samples larger than 30 increase the potential for the correlation analysis to provide meaningful results [348].

9.5 CONCLUSIONS

Changes in body weight confound all mass relative variables, particular from pre- to post-match where a reduction in body weight is likely to occur in soccer players due to fluid loss via perspiration. This is the first study to report that reductions in body weight confound the ability for outcome measures to be utilised alone for monitoring acute changes in NMF following a competitive soccer match in youth soccer players. The authors propose that there is no definitive CMJ measure that can determine acute changes in NMF following a competitive soccer match alone, but monitoring a combination of measures can help serve this purpose. Within the monitoring process, changes in body weight should always be monitored, given the statistical and meaningful changes identified in youth soccer players in this study, and given that force production relative to mass determines acceleration [15]. Additionally, utilising a combination of kinetic metrics (e.g., mean propulsive force, velocity, and power) and outcome metrics which are mass inclusive (e.g., jump momentum [or net propulsive impulse]) and relative to mass (e.g., TOV) would provide a holistic view about the effect of changes in body weight and NMF independently, and additional information about their effect on the overall outcome.

Changes in propulsive phase time have the potential to confound measures such as net propulsive impulse (i.e., jump momentum), but differences in propulsive phase time were minimally affected by competitive match-play in youth soccer players in this study. As the objective monitoring of changes in NMF via force plates has become more popular in soccer [161], particularly via the CMJ test [23], kinetic CMJ measures such as mean propulsive force, mean propulsive velocity, and mean propulsive power, jump momentum, and body weight might better explain acute changes in NMF following competitive match-play in youth soccer player. If utilising outcome measures in addition to these, collectively, these metrics will help to explain both if and why the outcome (e.g., JH) changes or remains the same following soccer match play, thus providing valuable context when utilizing the CMJ as an indicator of acute NMF. Determining statistical change on a group level via formal null significance hypotheses and magnitude testing (i.e., pairwise comparisons and ESs) helps to generalise the overall effects of a competitive match on the squad, but individual changes may vary from the group generalisation. Thus, meaningful changes may also be determined on an individual basis in practice via the application MDC statistics.

10 GENERAL DISCUSSION

The English FA's Four Corner Model provides a framework for coaches and trainers to develop soccer players in a holistic manner [10], where physical performance staff (e.g. sports scientists, S&C coaches, sports nutritionists) play an important role by focussing on optimising "*physical preparedness*" by following a cyclical "process of practice" of physical profiling, evaluation, reporting, and reviewing, which forms the basis of practice in the physical corner. Professional soccer players must endure the high physical demands of today's game and compete frequently with minimal recovery time (e.g., 48 to 72 hours later) due to congested fixture schedules [72, 74, 110]. Resultantly, physical coaches face the challenge of determining individual changes in physical preparedness through developments in fitness and the accumulation of fatigue following varying levels of individual external and internal workloads players must consistently produce, which manifest their own individual fitness and fatigue aftereffect response [73], and will result in non-uniform changes in the physical preparedness of players within a squad [95, 103, 109].

Wireless and portable force plate technology with validated hardware (as reported in chapter 6) [21] and proprietary software [20] has the potential to optimise the evaluation, reporting, and reviewing aspects of the process of practice in real-world settings, but only if best practices for the collection and analysis of objective testing information are established and prescribed across a range of tests and metrics of NMF, and reports are both informative and quick and easy to produce. The aim of this thesis was to evaluate and identify a best practice for force plate assessments for monitoring lower body NMF in soccer, which a soccer practitioner could utilise including test and metric selection, appropriate data collection and analysis procedures, statistical processes for determining objective benchmarks and observing meaningful change, and information regarding the practical application of these processes into real-world environments. To help with rationalising which tests and metrics are most appropriate to use, this thesis highlighted a plethora of methods, tests, and metrics which are available to practitioners who seek to use force plates to evaluate and monitor NMF in sport, and investigated them further by producing key information on the validity, within- and between-session reliability, meaningfulness (relation to sports specific actions), discriminatory capabilities (i.e., for objective benchmarking), and sensitivity to change (i.e., for monitoring acute changes) of specific tests and metrics.

10.1 Key Findings

The literature review and results of the scoping review pointed towards there being a variety of options of force plate testing application, but no general consensus on a best practice approach for the purpose of monitoring acute changes in NMF. As the CMJ was the most commonly utilised test in studies monitoring acute changes in NMF using force plates (as evidenced in the scoping review) and has been previously referenced as the most common test utilised in studies evaluating longitudinal changes in NMF [23], it was utilised within the validity study. It was concluded that the HD Inc. wireless dual force plate system can be considered valid for collecting CMJ force-time data, because no fixed or proportional bias was present for any CMJ variable (N = 17) when compared to an in-ground, laboratory grade, "gold standard", strain-gauge, AMTI force plate system. Thus, the CMJ test was utilised in subsequent investigations into the test-retest reliability of CMJ metrics in the pre-season period, which revealed acceptable reliability was demonstrated for 13 CMJ metrics for professional soccer players and five CMJ metrics for youth soccer players (Table 10.1). For comparison, acceptable reliability was demonstrated for 15 CMJ metrics for youth soccer players in-season period (Table 10.1), and because the monitoring of acute changes in NMF is most commonly performed in-season in sports around competitive matches (as evidenced in the scoping review), these 15 CMJ metrics were assessed in a real-world setting for their sensitivity to detect acute changes in NMF following an in-season competitive soccer match. Based on the results of the ANOVA, all metrics demonstrated sensitivity to change except peak propulsive force, where significant reductions in body weight immediately post-match (+15 min) confounds the ability for outcome measures (i.e., JH, FT, or TOV) to be utilised alone. Monitoring a combination of outcome, kinetic, and strategy measures was advised to help serve this purpose [23, 161].

When following a typical process of practice in the physical corner, physical profiling occurs immediately in the pre-season period (e.g., on the first day back) following the off-season break in professional soccer. Accordingly, 32 CMJ metrics were assessed for their applicability to be utilised as objective benchmarks. All CMJ metrics demonstrated acceptable within-session reliability and 25 of these discriminated between professional and youth soccer players in the pre-season period. It would be useful for physical coaches to know which CMJ metrics can be utilised both as objective benchmarks and within the fatigue monitoring process for soccer players to streamline practice, given the time constraints of data collection in real-world environments. Based on the abovementioned key findings, 11 CMJ metrics demonstrated utility to be used for both purposes, which included options of four outcome (JH, FT, jump momentum, and TOV) and five propulsive (mean propulsive force, mean propulsive velocity, peak velocity, peak propulsive power, and mean propulsive power) metrics, net braking impulse, and body weight (Table 10.1). On the contrary, some metrics can be considered for use for *only* a single purpose (i.e., for objective benchmarking *or* monitoring independently). Specifically, 14 CMJ metrics demonstrated utility to be used *only* as objective benchmarks (and not for monitoring) for professional and youth soccer players in the pre-season period. These included peak braking force, relative peak braking force, mean braking force, peak braking power, mean braking power, relative mean braking power, braking RFD, peak propulsive force, relative peak propulsive force, relative mean propulsive force, relative peak propulsive power, relative mean propulsive power, FT:CT, and mRSI. Three metrics demonstrated utility to be used *only* for in-season monitoring of acute changes in NMF (and not for objective benchmarking) for youth soccer players in the in-season period, which included countermovement depth, propulsive phase time, and net impulse ratio. This means that CMJ ratio metrics (i.e., FT:CT and mRSI) may *only* be proposed for objective benchmarking for professional and youth soccer players in the pre-season period, and CMJ strategy metrics (i.e., countermovement depth and propulsive phase time) can *only* be proposed for monitoring acute changes in NMF for youth soccer players in the in-season period.

Table 10.1. Summarised Findings of CMJ Metrics.

All Metrics	Valid?	Reliable? Pro Pre-Season	Reliable? Youth Pre-Season	Reliable? Youth In-Season	Disriminate? Pro vs Youth Pre-Season	Sensitive to Change? Youth In-Season
mRSI	Y	N	N	N	Y	N/A
FT:CT	N/A	N	N	N	Y	N/A
Jump Height	Y	Y	N	Y	Y	Y
Flight Time	Y	Y	N	Y	Y	Y
Jump Momentum	Y	Y	Y	Y	Y	Y
Takeoff Velocity	N/A	Y	N	Y	Y	Y
Time to Takeoff	Y	N	N	N	N	N/A
Stiffness	N/A	N	N	N/A	N/A	N/A
Net Impulse Ratio	N/A	N	N	Y	N	Y
Relative Mean Propulsive Power	N/A	N/A	N/A	N/A	Y	N/A
Mean Propulsive Power	Y	Y	Y	Y	Y	Y
Relative Peak Propulsive Power	N/A	N/A	N/A	N/A	Y	N/A
Peak Propulsive Power	Y	Y	Y	Y	Y	Y
Peak Velocity	Y	Y	N	Y	Y	Y
Mean Propulsive Velocity	N/A	Y	N	Y	Y	Y
Relative Mean Propulsive Force	N/A	N/A	N/A	N/A	Y	N/A
Mean Propulsive Force	Y	Y	Y	Y	Y	Y
Relative Peak Propulsive Force	N/A	N/A	N/A	N/A	Y	N/A
Peak Propulsive Force	Y	Y	N	Y	Y	N
Propulsive Phase Time	N/A	N	N	Y	N	Y
Force at Minimum Displacement	N/A	Y	N/A	N/A	N/A	N/A
Countermovement Depth	Y	N	N	Y	N	Y
Braking RFD	N/A	N	N	N	Y	N/A
Relative Mean Braking Power	N/A	N/A	N/A	N/A	Y	N/A
Mean Braking Power	Y	N	N	N	Y	N/A
Relative Peak Braking Power	N/A	N/A	N/A	N/A	N	N/A
Peak Braking Power	Y	N	N	N	Y	N/A
Mean Braking Velocity	N/A	N	N	N/A	N/A	N/A
Net Braking Impulse	Y	N	N	Y	Y	Y
Relative Mean Braking Force	N/A	N/A	N/A	N/A	N	N/A
Mean Braking Force	Y	N	N	N	Y	N/A
Relative Peak Braking Force	N/A	N/A	N/A	N/A	Y	N/A
Peak Braking Force	Y	Y	N	N	Y	N/A
Braking Phase Time	N/A	N	N	N	N	N/A
Unweighting Phase Time	N/A	N	N/A	N	N/A	N/A
Body Weight	Y	Y	Y	Y	Y	Y

Key: Y, Yes; N, No; N/A, Metric Not Assessed.

As the DJ was the most common RJ test utilised in studies monitoring acute changes in NMF using force plates (as evidenced in the scoping review), it was taken forward for the validity study. It was concluded that the HD Inc. wireless dual force plate hardware can be considered valid for collecting DJ force-time data, because fixed or proportional bias was present for only 2 out of 18 DJ variables, where percentage differences were considered small even at ~40% greater than grand mean values. Despite its validity, a proposed limitation to the DJ assessment is that previous research has reported differences between effective box height and actual fall height [169], and the validity study confirmed this as the mean effective fall height recorded during the DJ test was approximately 5 cm less than the prescribed 40 cm box height. Thus, the DJ test can only be prescribed as an assessment in physical profiling (i.e., for objective benchmarking) if future researchers, practitioners, and companies establish fall height during trials. To the author's knowledge, this would take a while to perform manually for every trial across all players within a squad it makes this test currently rather limited to use within a monitoring process because fast data turnaround is required. Furthermore, no meaningful DJ metrics demonstrated acceptable test-retest reliability for youth soccer players in the pre-season period, which made this test unsuitable to be taken forward for monitoring acute changes in NMF in this cohort. It was proposed in the reliability chapter that future research may consider exploring the applicability of alternative RJ tests (e.g., CMRJ test) which might eradicate the issues of fall height discrepancies seen in the DJ test. Therefore, the author chose to investigate the test-retest reliability of the CMRJ test (i.e., alternative RJ test where fall height is determined by a preceding CMJ) in youth soccer players.

Despite demonstrating acceptable reliability in CMJ portion TOV (i.e., which dictates the fall height in the RJ portion) and thus RJ portion net braking impulse (i.e., equal to landing momentum which is dictated by a multiplication of touchdown velocity and body mass), like the findings for the DJ test no meaningful RJ portion metrics demonstrated acceptable test-retest reliability for youth soccer players in the pre-season period. For comparison, the CMJ portion was performed with a reliable outcome (i.e., TOV and JH) and some RJ portion metrics (N = 5) demonstrated acceptable test-retest reliability in youth soccer players in the in-season period (i.e., FT, jump momentum TOV, mean propulsive force, and net braking impulse). The CMRJ test was not taken forward for the in-season monitoring study performed within this thesis primarily due to the lack of meaningful metric options which demonstrated reliability (i.e., only outcome metrics and mean propulsive force) in comparison to the CMJ test. Additionally, the feasibility of testing in a real-world environment only permits the application of a single easy to prescribe test, so the CMJ test was elected instead. However, these findings do open the potential for a determination of CMRJ metrics' sensitivity to acute change in NMF in future research with youth soccer players in the in-season period. As has been recommended in previous research [187, 189], the prescription of additional familiarisation to these tests may have improved the reliability of CMRJ metrics in these youth cohorts, therefore, a familiarisation period is strongly advised prior to data collection to permit reliable results. On the other hand, the CMRJ test provides a reliable RJ test option for physical profiling (i.e., objective benchmarking) as all the assessed CMJ portion (N = 5) and RJ portion (N = 25) metrics demonstrated acceptable within session reliability, and CMJ portion body weight and 20 RJ portion metrics discriminated between professional and youth soccer players in the pre-season period. These RJ portion metrics included two ratio (RSI and FT:CT), three outcome (JH, FT, and jump momentum), six propulsive (peak propulsive force, mean propulsive force, net impulse ratio, peak propulsive power, and mean and relative mean propulsive power), and nine braking (peak force, mean and relative mean braking force, net braking impulse, peak and relative peak braking power, mean and relative mean braking power, and braking depth) metrics. Practitioners may choose a variety of these metrics for objective benchmarking, but specific recommendations for practice are provided below in section 10.1.2 practical applications.

As the IMTP is the most common isometric test utilised for physical profiling and evaluating longitudinal changes in NMF [23], specifically relating to maximal absolute, relative, and rate of force production [187, 189], it was utilised in the within- and between-session reliability and objective benchmarking investigations of this thesis. After applying testing procedures in the reliability chapter (chapter 7) which are reflective of real-world practice, where testing was administered on the first and eighth day of pre-season players were coming from a six-to-eight-week off-season with no scheduled training, and youth soccer players resultantly had no familiarisation session prior to the test-retest data collection, no IMTP metrics demonstrated acceptable test-retest reliability for youth soccer players in the pre-season period. Therefore, the IMTP was not taken forward for monitoring acute changes in NMF in youth soccer players. Comfort et al. [187] suggested that although the optimal amount of familiarisation of the test has not yet been investigated, some form of familiarisation (e.g., a short session of submaximal trials approximately 48 hours before testing) should be provided prior to an IMTP testing session. This is corroborated by the findings of Musham et al. [270] who also reported that the absolute and relative reliability of IMTP metrics improved every week over four consecutive weeks (one testing session per week) in youth soccer players. Therefore, data collection could be improved in future research by providing familiarisation to youth soccer players in the pre-season period to improve IMTP metric reliability, so determinations regarding the utility of the IMTP as an option for monitoring acute changes in NMF can be made. Alternatively, all IMTP metrics demonstrated acceptable within-session reliability in professional and youth soccer players in the pre-season period, and peak force and relative peak force discriminated between and youth soccer players where professional soccer players produced significantly greater absolute and relative isometric force compared their youth counterparts. Therefore, practitioners can utilise the IMTP test for physical profiling where objective benchmarks for absolute and relative peak force collection may be produced for professional and youth soccer players in the pre-season period.

10.2 General Limitations

A common limitation to research performed in professional sports populations is small sample sizes [349]. The author planned to avoid this issue within this thesis, as exampled by producing and abiding to *a priori* sample size estimations in chapters 7 (test-retest reliability), 8 (objective benchmarking), and 9 (monitoring acute changes). As a strong example of this planning, the research presented in chapter 8 which focussed on producing normative data and objective benchmarks for professional and youth soccer players was performed by recruiting 7 separate professional EFL 2 clubs across three pre-season periods, totalling between 137-139 professional and 121-137 youth soccer players which accounts for 23-26% of the total maximum number of registered players with the EFL 2 within any given season. To the author's knowledge, this is the largest sample of professional and youth soccer players ever collated for the purposes of producing normative data, identifying discriminations in metrics between groups, and producing objective benchmarks for key force plate tests and metrics. Resultantly, this sample satisfied both the *a priori* determination of 45 subjects per group for comparisons, and the previously recommended 85 participants per group to satisfy suggestions for generating stable means and SDs for normative data [207]. Similarly, in chapter 9 the *a priori* sample size estimation produced for the repeated measures ANOVA across three independent testing timepoints was exceed by 9 subjects. However, a secondary analysis in chapter 9 was performed to establish relationships between changes in force plate metrics and the GPS value attained during the competitive match via Pearson's correlations. The sample used for the correlation analysis (N = 18) was seemingly too low to establish relationships, where it has been recommended that a minimum sample of 30 participants is required perform such statistical analyses [348]. The researcher could only attain GPS data for two squads out of the three squads which were tested for acute changes in NMF, simply because the staff responsible for collecting and analysing the data at one club could not provide accurate data. Thus, this limitation was out of the researcher's hands, but it may be a useful point for future research on the topic to perform fatigue monitoring research with consideration for both an *a priori* estimation and the minimum required sample for a correlation coefficient which could present interest data regarding the relations between external load parameters and measures of acute changes in NMF via force plate metrics.

The only experiment within this thesis that did not utilise a sports population was chapter 6 (validity). This was exercised due to testing being conducted early into this project where the effects of the coronavirus pandemic were still lingering, and social distancing and lockdowns were still prevalent. At this time, social contact between people was only allowed for colleagues where staff could only come on sight when they were teaching, and so recruitment was limited to staff and students around their timetables. Additionally, travel to sports organisations was prohibited for this reason, with football clubs frequently closing due to in-house outbreaks of the virus. Consequently, a convenience sampling approach was adopted where staff and students from the University of Salford were utilised for the study. Due to this sampling approach, an *a priori* estimation was not performed, but this research was continued under these circumstances as the researcher deemed it critical to continue the project in a timely manner, where the validation of the HD Inc. hardware was essential prior to trusting the data for subsequent studies, and it was a critical chapter of the project for the funder (i.e., HD Inc) to be the first fully validated system on the market (which was achieved following publication in May 2023). Finally, technique-intensive tests generally exhibit greater variability in results and require more pre-test practice to produce consistency, and therefore, greater reliability might be seen from an athlete with more experience with a task [36]. Resultantly, the prescription of additional familiarisation to force plate tests has been recommended in research to improve the reliability of metrics within a cohort [187, 189]. The testing conducted within this thesis was reflective of what occurs in real-world practice, particularly in the pre-season period where testing is conducted on the first day of pre-season without prior familiarisation. Additionally, it is important that when clubs are volunteering to conduct externally applied research that the researchers make testing as minimally invasive to the club schedules as possible, especially in-season. Despite all tests demonstrating good to excellent within-session reliability, whether an increase in familiarisation to the CMJ, DJ, CMRJ, and IMTP tests might improve the test-retest reliability of specific metric types (e.g., strategy and kinetic metrics) is unknown, which raises the opportunity for this to be assessed in a test-retest repeated measures design over a period of consecutive weeks.

10.3 Practical Applications

Previously, Bishop et al. [115] set out to provide practitioners with recommendations on which metrics to choose for both physical profiling and fatigue monitoring, assuming the metrics utilised for each purpose would be different. Recommendations were made on the selection of CMJ metrics for physical profiling based on considerations regarding their relation to field-based KPIs in sports (e.g., linear sprint and COD speed) [115], which is an important consideration along with an underpinning theory of physics (e.g., the biomechanical determinants of JH) [15]. However, when determining metrics to utilise for physical profiling (e.g., when objective benchmarking) it must also be considered whether said metrics discriminate between the comparative groups, and for fatigue monitoring (e.g., in response to match-play) it must be considered whether metrics demonstrate acceptable reliability and sensitivity to change, which are factors not considered in previous opinions on metric selection recommendations [115]. Firstly, body weight should be a metric that is monitored for acute changes (Table 10.2) as reductions in body weight immediately post a competitive professional [42] and youth (as reported in chapter 9) soccer match have been reported, likely due to perspiration. Therefore, the author considers mass relative outcome measures (e.g., JH, FT, and TOV) as not appropriate to utilise alone for monitoring acute changes in NMF, as changes in body mass will confound the measurement [42]. Body weight is also an important metric to monitor longitudinally for soccer players as clear differences were evident between professional and youth soccer players, however, producing objective benchmarks for body weight might not be suitable as publicising this within a squad can be a sensitive issue. Jump momentum (equal to mass multiplied by TOV) can instead be utilised as an objective benchmark as it discriminates between professional and youth soccer players and can provide valuable information regarding changes in and the interaction between body mass and TOV (Table 10.2). As jump momentum demonstrated acceptable test-retest reliability and sensitivity to change in youth soccer players in the in-season period, it can also be considered as a viable option for monitoring acute changes in NMF, and as it is equal to net propulsive impulse, it can provide valuable information regarding kinetic output. Body weight has not been considered in previous research providing metric selection recommendations for either profiling or fatigue monitoring aspects, however, net propulsive impulse (equal to jump momentum) has been proposed for performance profiling but not for fatigue monitoring [115], contrary to what has been recommended here.

Bishop et al. [115] recommended "time-based" metrics as theoretically appropriate for fatigue monitoring because they take into account a change in strategy performed to achieve the outcome (e.g., JH), proposing metrics such as propulsive phase time and time to take-off as viable options (Table 10.2). The author agrees with this theoretical suggestion but proposes the use of CMJ strategy measures such as countermovement depth and propulsive phase time for this purpose, as these metrics demonstrated acceptable reliability and sensitivity to change in youth soccer players in the in-season period (Table 10.2). Additionally, the author disagrees with suggestions by Bishop et al. [115] on the use of ratio metrics (e.g., mRSI or FT:CT) for fatigue monitoring which were proposed based on the same theoretical assumptions (i.e., the relevance of time-relative metrics) and previous suggestions for "linking metrics together" because it "enhances the ability to use all available information concurrently" [186]. Poor test-retest reliability was demonstrated for ratio metrics across all VJ tests assessed within this thesis, and thus ratio metrics were not taken forward for the monitoring study, so the author proposes that ratio metrics can be used *only* for profiling (Table 10.2) as mRSI and FT:CT ratio discriminated between professional and youth soccer players in the pre-season period, which is the opposite of what was proposed by Bishop et al. [115]. McMahon et al. [59] suggested the use of only one of mRSI or FT:CT is necessary given that the metrics provide theoretically similar information and demonstrate similarly acceptable reliability. Therefore, the author proposes formulating objective benchmarks for soccer players utilising mRSI (Table 10.2) given that the rationale for using force plates is utilising the more appropriate forward dynamics processes and the impulse-momentum theorem to equate TOV and estimate JH [230]. For the same reason, the authors proposes the use of JH as the elected mass-relative outcome metric for physical profiling (Table 10.2) given it discriminates between professional and youth soccer players in the pre-season period, is a component of mRSI [59], provides the same information as TOV (i.e., it is estimated via TOV) [230], and FT has a greater potential to be erroneous given that changes in plantar flexion at take-off and touch-down or tucking during the flight phase can artificially change the time of flight [59]. However, despite the popularity of JH in previous research on monitoring acute changes in NMF [23], the author suggests that JH may not be utilised as a primary metric of interest for monitoring acute changes in NMF as changes in body weight confound the metric's ability to do so, but can be prescribed in addition to other more appropriate kinetic and strategy metrics given it demonstrated acceptable test-retest reliability and sensitivity to change in youth soccer players in the in-season period (Table 10.2).

The author also disagrees with the notion by Bishop et al. [115] to only utilise time-based metrics for fatigue monitoring, as various kinetic metrics demonstrated acceptable reliability and sensitivity to change in youth soccer players in the in-season period, and discriminated between professional and youth soccer players in the pre-season period. Of the options available, the author specifically proposes the use of mean propulsive force and mean propulsive power for both fatigue monitoring and physical profiling (Table 10.2) as peak kinetic measures are largely influenced by changes in strategy, mean propulsive force is a component of mean propulsive power and net propulsive impulse (equal to jump momentum), the inclusion of mean propulsive force alongside mean propulsive power is sufficient to explain the interaction between mean propulsive force and mean propulsive velocity in relation to changes in mean propulsive power, and peak velocity provides practically similar information as TOV. Additionally, relative kinetic metrics can be utilised for physical profiling to give a fairer comparison of kinetic output capacity across a squad. Therefore, the author also proposes the creation of objective benchmarks for relative mean propulsive force and relative mean propulsive power for professional and youth soccer players in the pre-season period (Table 10.2). Braking kinetic metrics primarily demonstrated utility for profiling but are not proposed by the author for any purpose (Table 10.2). This is because net braking impulse is equal to and determined by one's braking momentum, which is a consequence of downward velocity and body mass. As downward velocity is determined via the starting height of the COM, which is determined by an athlete's stature and cannot be changed via training, and every athlete's body mass will differ, a comparison of braking momentum (i.e., net braking impulse) and any associated constituent force-time metrics across or between a squad of soccer players seems illogical. Additionally, as braking capacity is not maximised during a CMJ (because downward velocity is limited by standing COM height), it seems unsuitable to focus on these aspects of CMJ performance for physical profiling. Out of 28 CMJ metrics which can be utilised for physical profiling and/or monitoring acute changes in NMF, the author proposes practitioners utilise a combination of 10 metrics, which include jump momentum, mean propulsive power, and mean propulsive force for both purposes, plus the creation of objective benchmarks for mRSI, JH, relative mean propulsive power, and relative mean propulsive force for professional and youth soccer players in the pre-season period, and the utilisation of additional metrics such as propulsive phase time, countermovement depth, and body weight for monitoring youth soccer players' acute changes in NMF in the in-season period (Table 10.2). Despite JH and body weight being proposed for objective benchmarking and fatigue monitoring, respectively (see reasoning above), these metrics demonstrated utility to be used for both purposes and could be applied as such, depending on the rationale.

The CMRJ test can be applied for physical profiling as CMJ portion outcome measures demonstrated acceptable reliability and many RJ portion metrics (N = 25) discriminated between professional and youth soccer players in the pre-season period. For reasons highlighted above relating to metric selection for the CMJ test, the author proposes the use of a similar combination of seven ratio, outcome, and propulsive kinetic metrics to produce objective benchmarks for soccer players, including RJ portion RSI, JH, jump momentum, mean propulsive force, relative mean propulsive force, mean propulsive power, and relative mean propulsive power. The CMRJ test might also hold utility for monitoring in-season acute changes in NMF in youth soccer players as the CMJ portion was performed with a reliable outcome (i.e., TOV and JH) and some RJ portion metrics (N = 5) demonstrated acceptable test-retest reliability in youth soccer players in the in-season period (i.e., FT, jump momentum TOV, mean propulsive force, and net braking impulse), which could be investigated in future research. Practitioners can also utilise the IMTP test for physical profiling where objective benchmarks for absolute and relative peak force collection may be produced for professional and youth soccer players in the pre-season period. These best practice suggestions would cover a typical testing session for soccer players including tests and metrics relating to slow and fast SSC utilisation and measures of absolute and relative strength capacity.

Table 10.2. Countermovement Jump Metric Selection Options.

CMJ Metrics	PROFILING	COMBINED	MONITORING
Ratio	mRSI		
	FT:CT		
			Net Impulse Ratio
Outcome		Jump Height	
		Flight Time	
		Jump Momentum	
		Take-off Velocity	
Propulsive	Relative Mean Propulsive Power		
		Mean Propulsive Power	
	Relative Peak Propulsive Power		
		Peak Propulsive Power	
		Peak Velocity	
		Mean Propulsive Velocity	
	Relative Mean Propulsive Force		
		Mean Propulsive Force	
	Relative Peak Propulsive Force		
	Peak Propulsive Force		
			Propulsive Phase Time
Braking			Countermovement Depth
	Braking RFD		
	Relative Mean Braking Power		
	Mean Braking Power		
	Peak Braking Power		
		Net Braking Impulse	
	Mean Braking Force		
	Relative Peak Braking Force		
	Peak Braking Force		
Other		Body Weight	
Key: CMJ, countermovement Jump; bright green cell shading, recommended application.			

10.3.1 Recommended Reporting Guidelines

In addition to force plate test and metric selection recommendations which can be applied practically and in future research, there are many aspects of force plate testing data collection and analysis procedures which should be described more consistently in future research to allow for an accurate comparison of results (e.g., via meta-analysis) and for a better dissemination and translation of knowledge into practice [245]. Firstly, it is important that studies report details of a subject's demographics such as occupation or sport, sex, competitive level, and training and playing experience (Table 10.3). Without this primary information, results information cannot be grouped accordingly to be taken forward for meta-analysis and extrapolated to associated groups. As a brief example, McMahon et al. [28] assessed sex differences in the CMJ test, reporting that men performed a higher JH through applying greater propulsive impulse and TOV. This was achieved with men performing the task with a greater COM displacement but with a similar movement time to females [28]. Thus, it would be negligent to compare female to male CMJ performance, and as such, the reporting of demographic information in future research is essential (Table 10.3).

A consistent implementation of appropriate force plate data collection protocols is also critical to the fitness testing process to allow for accurate and reliable comparisons of data amongst published research [247]. For example, force plate models are typically selected in real-world practice based on their accessibility, feasibility, and affordability [247]. A minimum sample frequency of 1000 Hz has been recommended for the collection of force plate data in VJ tasks [248, 249], however, some force plate models are limited in their sampling frequency capability. Therefore, an appropriate model must be chosen and consistently applied across testing sessions [247]. Thus, it is important that researchers are transparent in future publications regarding the hardware and sampling frequency utilised so that research results can be utilised accordingly (Table 10.3). Additionally, it is important that details of familiarisation and warm-up protocols are reported in literature to provide confidence that the presented data represents "maximal" NMF during trials (Table 10.3).

The footwear utilised during force plate testing has a significant ($p < 0.05$) impact on force plate metrics such as peak vertical impact and braking force [250]. A failure to zero force plates between multiple trials can cause integration drift leading to erroneous data. Additionally, fluctuations in body weight due to inconsistencies during the weighing period of VJ trials would also compromise the reliability of metrics calculated via forward dynamics, specifically related to acceleration, velocity, and displacement [23]. The standardisation of verbal instructions and trial technique (including the utilisation of AS) is also vital to achieving accurate and reliable force-time data [247], as a differentiation in the verbal cues given to subjects will affect the force-time characteristics, CM depth adopted, movement time performed, and the resultant outcome of VJ tasks [184]. Taking all of this information into account, it seems critical that data collection procedures such as the hardware and sampling frequency used, time of the season that testing was conducted, prescribed familiarisation and warm-up protocols, the adopted processes of zeroing force plates between trials and weighing subjects during trials, the surface and footwear utilised, and the verbal cues provided to subjects before trials are reported in future research to allow for a replication of processes and provide readers with confidence in a study's results (Table 10.3).

Results from studies cannot be accurately compared without information regarding study design. As fatigue mechanisms work in different combinations, magnitudes, and timeframes throughout competition and during the recovery process [106], the most important factor to report in research monitoring acute changes in NMF is the testing time-points employed (Table 10.3). Where applicable, reporting quantitative measures of TL is useful as it provides objective information regarding athlete locomotion (i.e., external workload) and an individual's physiological response to it (i.e., internal workload) [254] (Table 10.3). In addition to the test and metric selection recommendations provided in section 10.3. practical applications, results data cannot be accurately compared across studies without the context of how metrics were calculated. Utilisation of the same metric terminologies for metrics with differing calculations, and the same metric calculations for metrics with differing terminologies, was reported across the studies identified in chapter 4 scoping review. This inconsistency makes data comparison (e.g., via meta-analysis) and the interpretation of information from current research in this area extremely difficult and unlikely. Future research should utilise and accurately describe appropriate metric terminologies and calculations to allow for future comparisons and meta-analyses of data to inform future practice (Table 10.3). To easily apply this recommendation, a validated approach is available via the HD Inc. force plate system's proprietary software [20].

Table 10.3. Reporting Guidelines for Future Research.

METHOD	CRITERION	RECOMMENDATION
Demographics	Sex	N/A
	Age	Report in y
	Height	Report in m
	Body Mass	Report in kg
	Occupation / Sport	N/A
	Competitive Level	N/A
	Training / Playing Experience	Report in y
Data Collection Protocols	Test(s)	See section 10.3. practical applications
	Time of Competitive Season	N/A
	Verbal Cues	N/A
	Surface Used	Solid and even (e.g., concrete)
	Footwear Worn	N/A
	Familiarisation to Test	N/A
	Pre-Testing Warm-Up	N/A
	Process of Zeroing Force Plates	See Hawkin Dynamics Inc. Metric Database (2023)
	Process of Weighing Subjects	
Hardware Information	Brand	A system which has been accuracy validated against a "gold standard"
	Model	
	Sampling Frequency	Minimum 1000 Hz
Study Design	Activity Performed	N/A
	Training Load Measures	N/A
	Baseline Testing Time-Points	A measure of central tendency and variability for all testing time-points
	Post-Activity Testing Time-Points	
Measures	Metric Definition	See Hawkin Dynamics Inc. Metric Database (2023)
	Metric Calculation	
	Phase Terminology	
	Phase Calculation	
Key: y, years; m, metres; kg, kilograms; N/A, not applicable; HZ, hertz.		

11 THESIS REFERENCES

1. Dunning, E., P. Murphy, and J. Williams, *The roots of football hooliganism, an historical and sociological study.* British Journal of Sociology, 1989. **40**: p. 343-344.
2. Maguire, J., *Global sport: Identities, societies, civilizations.* 1999: Blackwell Publishing.
3. Okholm Kryger, K., et al., *Research on women's football a scoping review.* Science and Medicine in Football, 2021: p. 1-10.
4. FIFA. *FIFA World Cup Qatar*. 2022; Available from: https://www.fifa.com/fifaplus/en/tournaments/mens/worldcup/qatar2022.
5. SportsProMedia. *Qatar 2022 World Cup final scores 1.5 bn global viewers.* 2023; Available from: https://www.sportspromedia.com/news/qatar-2022-fifa-world-cup-final-argentina-france-viewers-engagement/#:~:text=Argentina%27s%20shootout%20win%20over%20France,billion%20viewers%2C%20Fifa%20has%20revealed.
6. BBC. *World Cup 2022. Five trends from Qatar, upsets, injury time & penalties*. 2022; Available from: https://www.bbc.co.uk/sport/football/64027504.
7. Hall, D., D. James, and N. Marsden, *Marginal gains, Olympic lessons in high performance for organisations.* HR Bulletin Research and Practice, 2012. **7**(2): p. 9-13.
8. News, T.S. *How much prize money do the Premier League winners make? Full list of position prizes*. 2022; Available from: https://www.sportingnews.com/uk/Football/news/premier-league-prize-money-champions-full-table/ukfu5xbuzeogqcpvg0plkhe0.
9. Kelly, A., et al., *A multidisciplinary investigation into "playing-up" in academy football according to age phase.* J Sports Sci, 2021. **39**(8): p. 854-864.
10. Ford, P.R., et al., *The role of deliberate practice and play in career progression in sport: the early engagement hypothesis.* High ability studies, 2009. **20**(1): p. 65-75.
11. Williams, A.M. and T. Reilly, *Talent identification and development in soccer.* Journal of sports sciences, 2000. **18**(9): p. 657-667.
12. Triplett, N.T., *Structure and function of body systems*, in *Essentials of Strength Training and Conditioning, 4th ed.*, G.G. Haff and N.T. Triplett, Editors. 2016, Human Kinetics. p. 1-18.
13. Nédélec, M., et al., *Recovery in soccer part I, post-match fatigue and time course of recovery.* Sports medicine, 2012. **42**: p. 997-1015.
14. Wing, C.E., A.N. Turner, and C.J. Bishop, *Importance of strength and power on key performance indicators in elite youth soccer.* The Journal of Strength & Conditioning Research, 2020. **34**(7): p. 2006-2014.
15. Kirby, T.J., et al., *Relative Net Vertical Impulse Determines Jumping Performance.* Journal of Applied Biomechanics, 2011. **27**(3): p. 207-214.
16. Barr, M.J., J.M. Sheppard, and R.U. Newton, *Sprinting kinematics of elite rugby players.* J Aust Strength Cond, 2013. **21**(4): p. 14-20.
17. Bradley, P.S., et al., *Match performance and physical capacity of players in the top three competitive standards of English professional soccer.* Human movement science, 2013. **32**(4): p. 808-821.
18. Barnes, C., et al., *The evolution of physical and technical performance parameters in the English Premier League.* International journal of sports medicine, 2014. **35**(13): p. 1095-1100.
19. Comfort, P., P.A. Jones, and W.G. Hornsby, *Structured testing vs. continual monitoring*, in *Performance assessment in strength and conditioning*. 2018, Routledge. p. 42-50.

20. Merrigan, J.J., et al., *Analyzing Force-Time Curves: Comparison of Commercially Available Automated Software and Custom MATLAB Analyses.* Journal of Strength and Conditioning Research, 2022. **36**(9): p. 2387-2402.
21. Badby, A.J., et al., *The Validity of Hawkin Dynamics Wireless Dual Force Plates for Measuring Countermovement Jump and Drop Jump Variables.* Sensors, 2023. **23**(10): p. 4820.
22. Weldon, A., et al., *Contemporary practices of strength and conditioning coaches in professional soccer.* Biology of Sport, 2021. **38**(3): p. 377-390.
23. Guthrie, B., A.R. Jagim, and M.T. Jones, *Ready or Not, Here I Come: A Scoping Review of Methods Used to Assess Player Readiness Via Indicators of Neuromuscular Function in Football Code Athletes.* Strength & Conditioning Journal, 2022: p. 10.1519/SSC.0000000000000735.
24. Haff, G.G., et al., *A comparison of methods for determining the rate of force development during isometric midthigh clean pulls.* J Strength Cond Res, 2015. **29**(2): p. 386-95.
25. McMahon, J.J., et al., *Understanding the key phases of the countermovement jump force time curve.* Strength and Conditioning Journal, 2018. **40**(4): p. 96-106.
26. McMahon, J.J., et al., *Influence of the Reactive Strength Index Modified on Force- and Power-Time Curves.* International Journal of Sports Physiology and Performance, 2018. **13**(2): p. 220-227.
27. Mcmahon, J., et al., *Countermovement jump phase characteristics of senior and academy rugby league players.* Journal of Sports Physiology, 2016. **5**: p. 1-23.
28. Mcmahon, J., S. Rej, and P. Comfort, *Sex Differences in Countermovement Jump Phase Characteristics.* Sports, 2017.
29. Kurokawa, S., et al., *Interaction between fascicles and tendinous structures during counter movement jumping investigated in vivo.* Journal of applied physiology, 2003. **95**(6): p. 2306-2314.
30. Comfort, P. and J.J. McMahon, *Athlete Needs Analysis.*, in *Laboratory Manual for Strength and Conditioning.*, J. Miller, P. Comfort, and J.J. McMahon, Editors. 2023, Taylor & Francis.
31. James, L.P., et al., *Dimensionality reduction for countermovement jump metrics.* International Journal of Sports Physiology and Performance, 2021. **16**(7): p. 1052-1055.
32. Merrigan, J.J., et al., *Using Random Forest Regression to Determine Influential Force-Time Metrics for Countermovement Jump Height: A Technical Report.* Journal of Strength and Conditioning Research, 2022. **36**(1): p. 277-283.
33. Merrigan, J.J., et al., *Comparisons of Countermovement Jump Force-Time Characteristics Among National Collegiate Athletic Association Division I American Football Athletes: Use of Principal Component Analysis.* Journal of Strength and Conditioning Research, 2022. **36**(2): p. 411-419.
34. Merrigan, J.J., et al., *Dimensionality reduction differentiates sensitive force-time characteristics from loaded and unloaded conditions throughout competitive military training.* Sustainability, 2021. **13**(11): p. 6105.
35. Whitehead, S., et al., *The use of microtechnology to quantify the peak match demands of the football codes: A systematic review.* Sports Med, 2018. **48**: p. 2549-2575.
36. McGuigan, M., *Principles of test selection and administration.*, in *Essentials of Strength Training and Conditioning, 4th ed.*, G.G. Haff and N.T. Triplett, Editors. 2016. p. 249-258.
37. Emmonds, S., et al., *Physical characteristics of elite youth female soccer players characterized by maturity status.* The Journal of Strength & Conditioning Research, 2020. **34**(8): p. 2321-2328.

38. Emmonds, S., et al., *Influence of age on the anthropometric and performance characteristics of high level youth female soccer players.* International Journal of Sports Science & Coaching, 2018. **13**(5): p. 779-786.
39. Morris, R.O., et al., *Isometric midthigh pull characteristics in elite youth male soccer players. Comparisons by age and maturity offset.* The Journal of Strength & Conditioning Research, 2020. **34**(10): p. 2947-2955.
40. McMahon, J.J., et al., *Countermovement jump standards in rugby league: what is a good performance?* The Journal of Strength & Conditioning Research, 2022. **36**(6): p. 1691-1698.
41. McGuigan, M., *Administration, scoring, and interpretation of selected tests.*, in *Essentials of Strength Training and Conditioning, 4th ed.*, G.G. Haff and N.T. Triplett, Editors. 2016. p. 259-316.
42. Spencer, R., et al., *Changes in Body Mass and Movement Strategy Maintain Jump Height Immediately after Soccer Match.* Applied Sciences, 2023. **13**(12): p. 7188.
43. Bedo, B.L.S., et al., *The rapid recovery of vertical force propulsion production and postural sway after a specific fatigue protocol in female handball athletes.* Gait & Posture, 2020. **77**: p. 52-58.
44. Boullosa, D.A., et al., *Concurrent Fatigue and Potentiation in Endurance Athletes.* International Journal of Sports Physiology and Performance, 2011. **6**(1): p. 82-93.
45. Bromley, T., et al., *Effects of a Competitive Soccer Match on Jump Performance and Interlimb Asymmetries in Elite Academy Soccer Players.* J Strength Cond Res, 2021. **35**(6): p. 1707-1714.
46. Lonergan, B., et al., *The effect of fatigue on phase specific countermovement jump asymmetries in ACL-R and non-injured rugby union players.* Translational Sports Medicine, 2018. **1**(6): p. 238-249.
47. McCall, A., et al., *Reliability and sensitivity of a simple isometric posterior lower limb muscle test in professional football players.* Journal of Sports Sciences, 2015. **33**(12): p. 1298-1304.
48. Merrigan, J.J., *Effects of Maximal Effort Running on Special Agents' Loaded and Unloaded Drop Jump Performance and Mechanics.* Int J Environ Res Public Health, 2021. **18**(19).
49. McLellan, C.P. and D.I. Lovell, *Neuromuscular responses to impact and collision during elite rugby league match play.* J Strength Cond Res, 2012. **26**(5): p. 1431-40.
50. Furlan, L. and A. Sterr, *The applicability of standard error of measurement and minimal detectable change to motor learning research—a behavioral study.* Frontiers in human neuroscience, 2018. **12**: p. 95.
51. Lakens, D. *Improving Your Statistical Inferences.* 2022.
52. Thorlund, J.B., et al., *Acute fatigue-induced changes in muscle mechanical properties and neuromuscular activity in elite handball players following a handball match.* Scandinavian journal of medicine & science in sports, 2008. **18**(4): p. 462-472.
53. Oliver, J., N. Armstrong, and C. Williams, *Changes in jump performance and muscle activity following soccer-specific exercise.* Journal of sports sciences, 2008. **26**(2): p. 141-148.
54. Horita, T., et al., *Effect of exhausting stretch-shortening cycle exercise on the time course of mechanical behaviour in the drop jump: possible role of muscle damage.* European journal of applied physiology and occupational physiology., 1999. **79**(2): p. 160-167.
55. Clarke, N., et al., *Direct and indirect measurement of neuromuscular fatigue in Canadian football players.* Applied Physiology, Nutrition, and Metabolism, 2015. **40**(5): p. 464-473.

56. West, D.J., et al., *Neuromuscular function, hormonal, and mood responses to a professional rugby union match.* The Journal of Strength & Conditioning Research, 2014. **28**(1): p. 194-200.
57. Lake, J., et al., *Concurrent validity of a portable force plate using vertical jump force–time characteristics.* Journal of Applied Biomechanics, 2018. **34**(5): p. 410-413.
58. Badby, A.J., et al. *Between-Session Reliability of the Countermovement Jump and Countermovement Rebound Jump Tests in Youth Soccer Players, NSCA 2022 National Conference Abstracts*. in *The Journal of Strength & Conditioning Research*. 2022.
59. McMahon, J.J., J.P. Lake, and P. Comfort, *Reliability of and Relationship between Flight Time to Contraction Time Ratio and Reactive Strength Index Modified.* Sports (Basel), 2018. **6**(3).
60. Carroll, K.M., et al., *Intrasession and Intersession Reliability of Countermovement Jump Testing in Division-I Volleyball Athletes.* J Strength Cond Res, 2019. **33**(11): p. 2932-2935.
61. Comyns, T.M., et al., *Interday reliability and usefulness of a reactive strength index derived from 2 maximal rebound jump tests.* . International Journal of Sports Physiology and Performance. , 2019. **14**(9): p. 1200-1204.
62. Barnes, J.L., et al., *RELATIONSHIP OF JUMPING AND AGILITY PERFORMANCE IN FEMALE VOLLEYBALL ATHLETES.* Journal of Strength & Conditioning Research, 2007. **21**(4): p. 1192-1196.
63. Cronin, J.B. and K.T. Hansen, *Strength and power predictors of sports speed.* The Journal of Strength & Conditioning Research., 2005. **19**(2): p. 349-357.
64. Wells, J.E.T., et al., *Relationships Between Highly Skilled Golfers' Clubhead Velocity and Vertical Ground Reaction Force Asymmetry During Vertical Jumps and an Isometric Midthigh Pull.* J Strength Cond Res, 2020. **34**(10): p. 2824-2831.
65. Gathercole, R., et al., *Alternative Countermovement-Jump Analysis to Quantify Acute Neuromuscular Fatigue.* International Journal of Sports Physiology and Performance, 2015. **10**(1): p. 84-92.
66. Mcmahon, J., J. Lake, and P. Comfort, *Reliability of and Relationship between Flight Time to Contraction Time Ratio and Reactive Strength Index Modified.* Sports, 2018. **6**(3): p. 81.
67. Mcmahon, J., et al., *Relationship between reactive strength index variants in rugby league players.* The Journal of Strength & Conditioning Research, 2021. **35**(1): p. 280-285.
68. Mercer, R.A., et al., *Finding the Signal in the Noise—Interday Reliability and Seasonal Sensitivity of 84 Countermovement Jump Variables in Professional Basketball Players.* The Journal of Strength & Conditioning Research, 2022.
69. Heishman, A.D., et al., *Countermovement jump reliability performed with and without an arm swing in NCAA division 1 intercollegiate basketball players.* The Journal of Strength & Conditioning Research, 2020. **34**(2): p. 546-558.
70. Howarth, D.J., et al., *Establishing the Noise: Interday Ecological Reliability of Countermovement Jump Variables in Professional Rugby Union Players.* Journal of strength and conditioning research, 2021.
71. Selye, H., *The Stress of Life*. 1956, New York: McGraw-Hill.
72. Turner, A. and P. Comfort, *Periodisation*, in *Advanced Strength and Conditioning*, A. Turner and P. Comfort, Editors. 2017, Routledge. p. 116-136.
73. Haff, G.G., *Periodization*, in *Essentials of Strength Training and Conditioning, 4th ed.*, G.G. Haff and N.T. Triplett, Editors. 2016. p. 583-604.
74. Gabbett, T.J., *Workload monitoring and athlete management*, in *Advanced Strength and Conditioning*, A. Turner and P. Comfort, Editors. 2017, Routledge. p. 137-150.

75. Kiely, J., *Periodization paradigms in the 21st century: evidence-led or tradition-driven?* Int J Sports Physiol Perform, 2012. **7**(3): p. 242-250.
76. Stone, M.H. and A.C. Fry, *Increased training volume in strength/power athletes.* Overtraining in Sport, 1998. **87-105**.
77. Zatsiorsky, V.M., *Science and Practice of Strength Training*. 1995, Champaign, IL: Human Kinetics.
78. Chiu, L.Z. and J.L. Barnes, *The fitness-fatigue model revisited: Implications for planning short-and long-term training.* Strength & Conditioning Journal, 2003. **25**(6): p. 42-51.
79. Schoenfeld, B., *Mechanisms of Hypertrophy*, in *Science and Development of Muscle Hypertrophy 2nd Edition*. 2020, Human Kinetics. p. 30-56.
80. Prieske, O., et al., *Time to differentiate postactivation "potentiation" from "performance enhancement" in the strength and conditioning community.* Sports medicine, 2020. **50**(9): p. 1559-1565.
81. Blazevich, A.J. and N. Babault, *Post-activation potentiation versus post-activation performance enhancement in humans: historical perspective, underlying mechanisms, and current issues.* Frontiers in physiology, 2019. **10**: p. 479198.
82. Maroto-Izquierdo, S., I. Bautista, and F. Rivera, *Post-activation performance enhancement (PAPE) after a single-bout of high-intensity flywheel resistance training.* . Biology of Sport, 2020. **37**(4): p. 343-350.
83. Ciocca, G., H. Tschan, and A. Tessitore, *Effects of post-activation performance enhancement (PAPE) induced by a plyometric protocol on deceleration performance.* Journal of human kinetics, 2021. **80**(1): p. 5-16.
84. Boullosa, D., *Post-activation performance enhancement strategies in sport: a brief review for practitioners.* Human Movement, 2021. **22**(3): p. 101-109.
85. Cuthbert, M., et al., *Microdosing: A conceptual framework for use as programming strategy for resistance training in team sports.* Strength & Conditioning Journal, 2022: p. 10-1519.
86. Harrison, P.W., et al., *Resistance priming to enhance neuromuscular performance in sport: evidence, potential mechanisms and directions for future research.* Sports Medicine, 2019. **49**(10): p. 1499-1514.
87. Harrison, P.W., et al., *Prevalence and application of priming exercise in high performance sport.* Journal of science and medicine in sport, 2020. **23**(3): p. 297-303.
88. Häkkinen, K., M. Alén, and P.V. Komi, *Changes in isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining.* Acta Physiol. Scand., 1985. **125**(4): p. 573-585.
89. Häkkinen, K., M. Alén, and P.V. Komi, *Effect of explosive type strength training in isometric force- and relaxationtime, electromyographic and muscle fibre characteristics of leg extensor muscles.* Acta Physiol. Scand., 1985. **125**: p. 587-600.
90. Izquierdo, M., et al., *Effects of long-term training specificity on maximal strength and power of the upper and lower extremities in athletes from different sports. Eur. J. Appl. Physiol. 87:264–271.* Eur J Appl Physiol, 2002. **87**: p. 267-271.
91. Staron, R.S., et al., *Skeletal muscle adaptations during early phase of heavy-resistance training in men and women.* Journal of Applied Physiology, 1994. **76**: p. 1247-1255.
92. McArdle, W.D., F.I. Katch, and V.L. Katch, *Exercise Physiology: Energy, Nutrition, and Human Performance*. 1996, Baltimore: Williams & Wilkins.
93. Malone, J.J., et al., *Unpacking the black box: applications and considerations for using GPS devices in sport.* International journal of sports physiology and performance, 2017. **12**(2): p. 2-18.

94. Gabbett, T., et al., *The athlete monitoring cycle: A practical guide to interpreting and applying training monitoring data.* Br J Sports Med, 2017. **51**(1451-1452).
95. Bangsbo, J., M. Mohr, and P. Krustrup, *Physical and metabolic demands of training and match-play in the elite football player.* Journal of sports sciences, 2006. **24**(7): p. 665-674.
96. Russell, M., et al., *Changes in acceleration and deceleration capacity throughout professional soccer match-play.* Journal of strength and conditioning research, 2016. **30**(10): p. 2839-2844.
97. Bradley, P.S., et al., *The effect of high and low percentage ball possession on physical and technical profiles in English FA Premier League soccer matches.* Journal of sports sciences, 2013. **31**(12): p. 1261-1270.
98. Lupo, C., et al., *Internal-Training-Load Monitoring, Notational and Time-Motion Analyses, Psychometric Status, and Neuromuscular Responses in Elite Rugby Union.* Int J Sports Physiol Perform, 2021. **16**(3): p. 421-428.
99. Bangsbo, J., F.M. Iaia, and P. Krustrup, *Metabolic response and fatigue in soccer.* International journal of sports physiology and performance, 2007. **2**(2): p. 111-127.
100. McBurnie, A.J. and T. Dos'Santos, *Multidirectional Speed in Youth Soccer Players: Theoretical Underpinnings.* Strength and Conditioning Journal, 2022. **14**(1): p. 15-33.
101. McBurnie, A.J., et al., *Multidirectional speed in youth soccer players: Programming considerations and practical applications.* Strength and Conditioning Journal, 2022. **44**(2): p. 10-32.
102. Komi, P.V. and J.T. Viitasalo, *Changes in motor unit activity and metabolism in human skeletal muscle during and after repeated eccentric and concentric contractions.* Acta Physiol. Scand., 1977. **100**: p. 246-254.
103. Herda, T.J. and J.T. Cramer, *Bioenergetics of exercise and training.*, in *Essentials of strength training and conditioning, 4th ed.*, G.G. Haff and N.T. Triplett, Editors. 2016, Human Kinetics: Champaign, IL. p. 43-64.
104. Robergs, R.A., F. Ghiasvand, and D. Parker, *Biochemistry of exercise-induced metabolic acidosis.* American Journal of Physiology-Regulatory, Integrative and Comparative Physiology., 2004.
105. Fitts, R., *The Role of Acidosis in Fatigue: Pro Perspective.* Medicine & Science in Sports & Exercise, 2016. **48**(11).
106. Mohr, M., P. Krustrup, and J. Bangsbo, *Fatigue in soccer: a brief review.* Journal of sports sciences, 2005. **23**(6): p. 593-599.
107. Zając, A., et al., *Central and peripheral fatigue during resistance exercise–a critical review.* Journal of human kinetics, 2015. **49**: p. 159.
108. Edwards, A.M. and N.A. Clark, *Thermoregulatory observations in soccer match play: professional and recreational level applications using an intestinal pill system to measure core temperature.* British journal of sports medicine, 2006. **40**(2): p. 133.
109. Barber-Westin, S.D. and F.R. Noyes, *Effect of fatigue protocols on lower limb neuromuscular function and implications for anterior cruciate ligament injury prevention training: a systematic review.* The American Journal of Sports Medicine, 2017. **45**(14): p. 3388-3396.
110. Carling, C., et al., *Match running performance during fixture congestion in elite soccer: research issues and future directions.* Sports Medicine, 2015. **45**: p. 605-613.
111. Linthorn, N., *Analysis of standing vertical jumps using a force platform.* American Journal of Physics, 2001. **69**(11): p. 1198-1204.
112. Suchomel, T.J. and P. Comfort, *Developing muscular strength and power*, in *Advanced Strength and Conditioning: An Evidence-Based Approach.* 2018. p. 13-38.

113. McMahon, J.J., et al., *Influence of the reactive strength index modified on force– and power–time curves.* International Journal of Sports Physiology and Performance, 2018. **13**(2): p. 220-227.
114. McMahon, J.J., N.J. Ripley, and P. Comfort, *Force plate derived countermovement jump normative data and benchmarks for professional Rugby League players.* Sensors, 2022. **22**(22): p. 8669.
115. Bishop, C., et al., *Selecting Metrics That Matter: Comparing the Use of the Countermovement Jump for Performance Profiling, Neuromuscular Fatigue Monitoring, and Injury Rehabilitation Testing.* Strength & Conditioning Journal, 2022: p. 10-1519.
116. Gathercole, R.J., T. Stellingwerff, and B.C. Sporer, *Effect of acute fatigue and training adaptation on countermovement jump performance in elite snowboard cross athletes.* The Journal of Strength & Conditioning Research, 2015. **29**(1): p. 37-46.
117. Nicol, C., J. Avela, and P.V. Komi, *The stretch-shortening cycle.* Sports medicine, 2006. **36**(11): p. 977-999.
118. Mcmahon, J., *Stretch-Shortening Cycle and Muscle-Tendon Stiffness*, in *Advanced Strength and Conditioning: An Evidence-Based Approach*. 2017. p. 39-55.
119. Bobbert, M.F., et al., *Why is countermovement jump height greater than squat jump height?* Med Sci Sports Exerc, 1996. **28**(11): p. 1402-1412.
120. Fiorenza, M., et al., *Neuromuscular fatigue and metabolism during high-intensity intermittent exercise.* Medicine and science in sports and exercise, 2019. **51**(8): p. 1642-1652.
121. Gandevia, S.C., *Some central and peripheral factors affecting human motoneuronal output in neuromuscular fatigue.* Sports medicine, 1992. **13**: p. 93-98.
122. Davis, J.M. and S.P. Bailey, *Possible mechanisms of central nervous system fatigue during exercise.* . Medicine and science in sports and exercise, 1997. **29**(1): p. 45-57.
123. Sieck, G.C. and Y.S. Prakash, *Fatigue at the neuromuscular junction, branch point vs. presynaptic vs. postsynaptic mechanisms.* Fatigue: Neural and muscular mechanisms., 1995: p. 83-100.
124. Cè, E., et al., *Peripheral fatigue: new mechanistic insights from recent technologies.* European journal of applied physiology, 2020. **120**(1): p. 17-39.
125. Amann, M., *Significance of Group III and IV muscle afferents for the endurance exercising human.* Clin Exp Pharmacol Physiol., 2012. **39**(9): p. 831-835.
126. McCord, J.L. and M.P. Kaufman, *Reflex Autonomic Responses Evoked by Group III and IV Muscle Afferents.*, in *Translational pain research: from mouse to man.*, L. Kruger and A.R. Light, Editors. 2009, CRC Press: Boca Raton, Florida. p. 283.
127. Brancaccio, P., N. Maffulli, and F.M. Limongelli, *Creatine kinase monitoring in sport medicine.* British medical bulletin, 2007. **81**(1): p. 209-230.
128. Faude, O., W. Kindermann, and T. Meyer, *Lactate threshold concepts: how valid are they?.* Sports medicine, 2009. **39**: p. 469-490.
129. Warren, G.L., D.A. Lowe, and R.B. Armstrong, *Measurement tools used in the study of eccentric contraction-induced muscle injury.* Sports Med, 1999. **27**: p. 43-59.
130. Taylor, K., et al., *Fatigue monitoring in high performance sport: a survey of current trends.* J Aust Strength Cond, 2012. **20**(1): p. 12-23.
131. Talpey, S.W., et al., *Changes in Lower Body Muscular Performance Following a Season of NCAA Division I Men's Lacrosse.* Sports (Basel), 2019. **7**(1).
132. Liebermann, D.G., M.E. Maitland, and L. Katz, *Lower-limb extension power: How well does it predict short distance speed skating performance?* Isokinetics and Exercise Science, 2002. **10**(2): p. 87-95.

133. Moreira, P.V.S., M.F. Goethel, and M. Gonçalves, *Neuromuscular performance of Bandal Chagui: Comparison of subelite and elite taekwondo athletes.* Journal of Electromyography & Kinesiology, 2016. **30**: p. 55-65.
134. Wallmann, H.W., J.A. Mercer, and M.R. Landers, *Surface electromyographic assessment of the effect of dynamic activity and dynamic activity with static stretching of the gastrocnemius on vertical jump performance.* Journal of strength and conditioning research, 2008. **22**(3): p. 787-793.
135. Kang, M.S., J. Kim, and J. Lee, *Effect of different muscle contraction interventions using an isokinetic dynamometer on muscle recovery following muscle injury.* Journal of exercise rehabilitation, 2018. **14**(6): p. 1080.
136. O'Malley, E., et al., *Countermovement jump and isokinetic dynamometry as measures of rehabilitation status after anterior cruciate ligament reconstruction.* Journal of athletic training, 2018. **53**(7): p. 687-695.
137. Buśko, K., et al., *Leg strength and power in Polish striker soccer players.* Acta Bioeng Biomech, 2018. **20**(2): p. 109-116.
138. Sundstrup, E., et al., *Positive effects of 1-year football and strength training on mechanical muscle function and functional capacity in elderly men.* Eur J Appl Physiol, 2016. **116**(6): p. 1127-38.
139. Chamari, K., et al., *The five-jump test for distance as a field test to assess lower limb explosive power in soccer players.* J Strength Cond Res, 2008. **22**(3): p. 944-50.
140. Cleak, M.J. and R.G. Eston, *Muscle soreness, swelling, stiffness and strength loss after intense eccentric exercise.* British Journal of Sports Medicine, 1992. **26**: p. 267-272.
141. Howell, J.N., G. Chleboun, and R. Conatser, *Muscle stiffness, strength loss, swelling and soreness following exercise-induced injury in humans.* Journal of Physiology, 1993. **464**: p. 183-196.
142. Davies, C.T.M. and M.J. White, *Muscle weakness following eccentric work in man.* Pflugers Arch, 1981(392): p. 168-171.
143. Viitasalo, J.T., P.V. Komi, and I. Jacobs, *Effects of prolonged cross-country skiing on neuromuscular performance,* in *Exercise and Sport Biology*, P.V. Komi, Editor. 1982, Human Kinetics: Champaign, IL. p. 191-198.
144. Nicol, C., P.V. Komi, and P. Marconnet, *Fatigue effects of marathon running on neuromuscular performance: I. changes in muscle force and stiffness characteristics.* Scandinavian Journal of Medicine and Science in Sports, 1991. **1**: p. 10-17.
145. Millet, G.Y., R. Lepers, and N.A. Maffiuletti, *Alterations of neuromuscular function after an ultramarathon.* Journal of Applied Physiology, 2002. **92**: p. 486-492.
146. Avela, J., H. Kyrolainen, and P.V. Komi, *Reduced reflex sensitivity persists several days after long-lasting stretch-shortening cycle exercise.* Journal of Applied Physiology, 1999. **86**: p. 1292-1300.
147. Byrne, C. and R. Etson, *Maximal intensity isometric and dynamic exercise performance following eccentric muscle actions.* Journal of Sports Science, 2002. **20**: p. 951-959.
148. Byrne, C., C. Twist, and R. Eston, *Neuromuscular function after exercise-induced muscle damage.* Sports Medicine, 2004. **34**(1): p. 49-69.
149. Byrne, C., R. Eston, and R.H.T. Edwards, *Characteristics of isometric and dynamic strength loss following eccentric exercise-induced muscle damage.* Scandinavian Journal of Medicine and Science in Sports, 2001. **11**: p. 134-140.
150. Child, R.B., J.M. Saxton, and A.E. Donnelly, *Comparison of knee extensor muscle actions on indices of damage and angle-specific force production in humans.* Journal of Sports Science, 1998. **16**: p. 301-308.

151. Saxton, J.M. and A.E. Donnelly, *Length-specific impairment of skeletal muscle contractile function after eccentric muscle actions in man.* Clinical Science, 1996. **90**: p. 119-125.
152. Jones, C., T. Allen, and J. Talbot, *Changes in the mechanical properties of human and amphibian muscle after eccentric exercise.* Eur J Appl Physiol, 1997. **76**: p. 21-31.
153. Morgan, D.L. and D.G. Allen, *Early events in stretch-induced muscle damage.* Journal of Applied Physiology, 1999. **87**: p. 2007-2015.
154. Byrne, C. and R. Eston, *The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance.* Journal of Sports Science, 2002. **20**: p. 417-425.
155. Hortobagyi, T., J. Houmard, and D. Fraser, *Normal forces and myofibrillar disruption after repeated eccentric exercise.* Journal of Applied Physiology, 1998. **84**: p. 492-498.
156. Michaut, A., M. Pousson, and N. Babault, *Is eccentric exercise-induced torque decrease contraction type dependent?* Med Sci Sports Exerc, 2002. **34**: p. 1003-1008.
157. Baltzopoulos, V. and N.P. Gleeson, *Skeletal Muscle Function*, in *Kinanthropometry and exercise physiology laboratory manual: tests, procedures and data*, R. Eston and T. Reilly, Editors. 2001, Routledge: London. p. 7-35.
158. Komi, P.V., *Stretch-shortening cycle: a powerful model to study normal and fatigued muscle.* Journal of Biomechanics, 2000. **33**: p. 1197-1206.
159. Rowell, A., et al., *A standardized small sided game can be used to monitor neuromuscular fatigue in professional A-league football players.* Front Physiol, 2018. **9**: p. 1011.
160. Weldon, A., et al., *Contemporary practices of strength and conditioning coaches in professional cricket.* International Journal of Sports Science & Coaching, 2021. **16**(3): p. 585-600.
161. Weldon, A., et al., *Contemporary practices of strength and conditioning coaches in professional soccer.* Biology of Sport, 2021. **38**(3): p. 377-390.
162. McMahon, J.J., et al., *Understanding the key phases of the countermovement jump force-time curve. 2018;40(4):96–106.* Strength and Conditioning Journal, 2018. **40**(4): p. 96-106.
163. Badby, A.J., et al. *Agreement among countermovement jump force-time variables obtained from a wireless dual force plate system and an industry gold standard system.* in *International Society of Biomechanics in Sports*. 2022. Liverpool, UK.
164. McKay, A.K., et al., *Defining training and performance caliber: a participant classification framework.* International journal of sports physiology and performance, 2021. **17**(2): p. 317-331.
165. McMahon, J.J., P.A. Jones, and P. Comfort, *Comparison of Countermovement Jump-Derived Reactive Strength Index Modified and Underpinning Force-Time Variables Between Super League and Championship Rugby League Players.* J Strength Cond Res, 2022. **36**(1): p. 226-231.
166. McLellan, C.P., D.I. Lovell, and G.C. Gass, *Performance analysis of elite rugby league match play using global positioning systems.* Journal of Strength & Conditioning Research, 2011. **25**(6): p. 1703-1710.
167. Maloney, S.J., J. Richards, and I.M. Fletcher, *A Comparison of Bilateral and Unilateral Drop Jumping Tasks in the Assessment of Vertical Stiffness.* Journal of Applied Biomechanics, 2018. **34**(3): p. 199-204.
168. Markwick, W.J., et al., *The intraday reliability of the reactive strength index calculated from a drop jump in professional men's basketball.* International Journal of Sports Physiology and Performance, 2015. **10**(4): p. 482-488.

169. Costley, L., et al., *Reliability of bounce drop jump parameters within elite male rugby players.* J Sports Med Phys Fitness, 2018. **58**(10): p. 1390-1397.
170. Geraldo, G., et al., *Drop height is influenced by box height but not by individual stature during drop jumps.* Journal of Physical Education, 2019.
171. McMahon, J.J., et al., *A proposed method for evaluating drop jump performance with one force platform.* Biomechanics, 2021. **1**(2): p. 178-189.
172. Stratford, C., T. Santos, D., and J. Mcmahon, *The 10/5 repeated jumps test: are 10 repetitions and three trials necessary?* 2021: p. 0-14.
173. Xu, J., et al., *Countermovement Rebound Jump: A Comparison of Joint Work and Joint Contribution to the Countermovement and Drop Jump Tests.* Applied Sciences, 2023. **13**(19): p. 10680.
174. Browne, D. and E. Flanagan, *Reactive Strength Endurance: Part 1. The response of reactive strength to fast stretch-shortening cycle fatigue.* Sports Performance and Science Reports, 2018. **1**: p. 1–3. .
175. Lloyd, R.S., et al., *Reliability and validity of field-based measures of leg stiffness and reactive strength index in youths.* Journal of Sports Sciences, 2009. **27**(14): p. 1565-1573.
176. Xu, J., et al., *The Countermovement Rebound Jump: Between-Session Reliability and a Comparison With the Countermovement and Drop Jump Tests.* The Journal of Strength & Conditioning Research, 2022: p. 10-1519.
177. Hay, J.G. and J.G. Reid, *Anatomy, mechanics, and human motion.* 2 ed. ed. 1988: Prentice Hall.
178. Badby, A.J. and J.J. McMahon, *The Comparison of Self-Selected Squat Depth in Countermovement Jumps vs Standardised Squat Jump Methods: Implications for the Calculation of the Eccentric Utilisation Ratio.* Unpublished Manuscript, 2018.
179. Badby, A.J. and J.J. Mcmahon, *The Effects of Verbal Instruction on Countermovement Jump Phase Kinetics.* Unpublished Manuscript, 2017.
180. Badby, A.J. and J.J. Mcmahon, *The Effects of Arm Swing on Vertical Jump Kinetics and Kinematics.* Unpublished Manuscript, 2018.
181. Badby, A.J. and J.J. Mcmahon, *Influence of Performing Squat Jumps from a Standardised Depth Versus the Same Depth as Countermovement Jumps on Eccentric Utilisation Ratio.* Unpublished Manuscript, 2018.
182. Porter, J., W. Wu, and J. Partridge, *Focus of attention and verbal instructions: Strategies of elite track and field coaches and athletes.* Sports Science Review, 2010.
183. Sanchez-Sixto, A., J.J. Mcmahon, and P. Floria, *Verbal Instructions Affect Reactive Strength Index Modified and Time-Series Waveforms in Basketball Players.* Sports Biomechanics, 2021. **00**(00): p. 1-11.
184. Jidovtseff, B., et al., *Influence of jumping strategy on kinetic and kinematic variables.* J Sports Med Phys Fitness, 2014. **54**(2): p. 129-38.
185. Mcmahon, J., et al., *Vertical jump testing in rugby league: A rationale for calculating take-off momentum.* Journal of Applied Biomechanics, 2020. **36**(6): p. 370-374.
186. Bishop, C., et al., *A framework to guide practitioners for selecting metrics during the countermovement and drop jump tests.* Strength & Conditioning Journal, 2022. **44**(4): p. 95-103.
187. Comfort, P., et al., *Standardization and methodological considerations for the isometric midthigh pull.* Strength & Conditioning Journal, 2019. **41**: p. 57-79.
188. Dos'Santos, T., et al., *EFFECT OF DIFFERENT ONSET THRESHOLDS ON ISOMETRIC MIDTHIGH PULL FORCE-TIME VARIABLES.* Journal of Strength and Conditioning Research, 2017. **31**(12): p. 3463-3473.

189. Dos'Santos, T., et al., *Between-session reliability of isometric midthigh pull kinetics and maximal power clean performance in male youth soccer players.* The Journal of Strength & Conditioning Research, 2018. **32**(12): p. 3364-3372.
190. McMahon, J.J., et al., *Influence of Dynamic Strength Index on Countermovement Jump Force-, Power-, Velocity-, and Displacement-Time Curves.* Sports (Basel), 2017. **5**(4).
191. Beckham, G., S. Mizuguchi, and C. Carter, *Relationships of isometric mid-thigh pull variables to weightlifting performance.* The Journal of Sports Medicine and Physical Fitness, 2013. **53**(5): p. 573-581.
192. Haff, G., et al., *Force-time curve characteristics of dynamic and isometric muscle actions of elite women olympic weightlifters.* Journal of Strength & Conditioning Research, 2005. **19**(4): p. 741.
193. Haff, G., et al., *Force-time dependent characteristics of dynamic and isometric muscle actions.* The Journal of Strength & Conditioning Research, 1997. **11**(4): p. 269-272.
194. McGuigan, M. and J. Winchester, *The relationship between isometric and dynamic strength in college football players.* Journal of Sports Science and Medicine, 2008. **7**(1): p. 101.
195. Thomas, C., et al., *Relationship between Isometric Strength, Sprint, and Change of Direction Speed in Male Academy Cricketers.* Journal of Trainology, 2016. **5**(2): p. 18-23.
196. West, D., et al., *Relationships between force–time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players.* Journal of Strength & Conditioning Research, 2011. **25**(11): p. 3070-3075.
197. Comfort, P., et al., *Changes in dynamic strength index in response to strength training.* Sports, 2018. **6**(4): p. 176.
198. Kawamori, N., et al., *Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities.* The Journal of Strength & Conditioning Research, 2006. **20**(3): p. 483-491.
199. Thomas, C., et al., *Relationship between isometric mid-thigh pull variables and sprint and change of direction performance in collegiate athletes.* Journal of trainology, 2015. **4**(1): p. 6-10.
200. Spiteri, T., et al., *Contribution of strength characteristics to change of direction and agility performance in female basketball athletes.* The Journal of Strength & Conditioning Research, 2014. **28**(9): p. 2415-2423.
201. Tears, C., P. Chesterton, and M. Wijnbergen, *The elite player performance plan: the impact of a new national youth development strategy on injury characteristics in a premier league football academy.* Journal of sports sciences, 2018. **36**(19): p. 2181-2188.
202. Swinton, P.A., et al., *A Statistical Framework to Interpret Individual Response to Intervention: Paving the Way for Personalized Nutrition and Exercise Prescription.* Frontiers in Nutrition, 2018. **5**.
203. Shrout, P.E. and J.L. Fleiss, *Intraclass correlations: uses in assessing rater reliability.* Psychol Bull, 1979. **86**(2): p. 420-8.
204. Koo, T.K. and M.Y. Li, *A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research.* J Chiropr Med, 2016. **15**(2): p. 155-63.
205. Mundy, P.M. and N.D. Clarke, *Reliability, validity and measurement error*, in *Performance assessment in strength and conditioning*. 2018, Routledge. p. 23-33.
206. Heishman, A.D., et al., *Countermovement Jump Reliability Performed With and Without an Arm Swing in NCAA Division 1 Intercollegiate Basketball Players.* Journal of Strength and Conditioning Research, 2020. **34**(2): p. 546-558.

207. Piovesana, A. and G. Senior, *How small is big: Sample size and skewness.* Assessment, 2018. **25**(6): p. 793-800.
208. Bridges, A.J. and K.A. Holler, *How many is enough? Determining optimal sample sizes for normative studies in pediatric neuropsychology.* Child Neuropsychology, 2007. **13**(6): p. 528-538.
209. Lydersen, S., *Mean and standard deviation or median and quartiles?* Tidsskrift for Den norske legeforening., 2020.
210. Leech, N.L. and A.J. Onwuegbuzie, *A Call for Greater Use of Nonparametric Statistics.*, in *The annual meeting of the Mid-South Educational Research Association*. 2002: Chattanooga, TN.
211. Kim, H.Y., *Statistical notes for clinical researchers: assessing normal distribution (2) using skewness and kurtosis.* Restorative dentistry & endodontics, 2013. **38**(1): p. 52-54.
212. Fritz, C.O., P.E. Morris, and J.J. Richler, *Effect size estimates: current use, calculations, and interpretation.* Journal of experimental psychology, 2012. **141**(1): p. 2.
213. Lakens, D., *Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs.* Frontiers in psychology, 2013. **4**: p. 863.
214. Cohen, J., *The analysis of variance and covariance.*, in *Statistical Power Analysis for the Behavioral Sciences.* 1988, Routledge Academic: New York, NY, USA. p. 273-406.
215. Ludbrook, J., *Statistical techniques for comparing measurers and methods of measurement: a critical review.* Clinical and Experimental Pharmacology and Physiology, 2002. **29**(7): p. 527-536.
216. Bourdon, P., et al., *Monitoring athlete training loads: Consensus statement.* Int J Sports Physiol Perform, 2017. **12**: p. 2161-2170.
217. Opar, D.A., et al., *Eccentric hamstring strength and hamstring injury risk in Australian footballers.* Medicine & Science in Sports & Exercise, 2015. **47**(4): p. 857-865.
218. Opar, D.A., et al., *Is pre-season eccentric strength testing during the Nordic hamstring exercise associated with future hamstring strain injury? A systematic review and meta-analysis.* Sports Medicine, 2021. **51**(9): p. 1935-1945.
219. Campbell, P., et al., *The effect of overreaching on neuromuscular performance and wellness responses in Australian rules football athletes.* J Strength Cond Res, 2020. **34**: p. 1530-1538.
220. Los Arcos, A., et al., *Negative associations between perceived training Load, volume and changes in physical fitness in professional soccer players.* J Sport Sci Med, 2015. **14**: p. 394-401.
221. Kipp, K., et al., *Biomechanical Determinants of the Reactive Strength Index During Drop Jumps.* International Journal of Sports Physiology and Performance, 2018. **13**(1): p. 44-49.
222. Merrigan, J.J., et al., *Monitoring Neuromuscular Performance in Military Personnel.* Int J Environ Res Public Health, 2020. **17**(23).
223. Leduc, C., et al., *Convergent validity, reliability, and sensitivity of a running test to monitor neuromuscular fatigue.* Int J Sports Physiol Perform, 2020. **15**: p. 1-7.
224. Oliver, J., R. Lloyd, and A. Whitney, *Monitoring of in- season neuromuscular and perceptual fatigue in youth rugby players.* Eur J Sport Sci, 2015. **15**: p. 514-522.
225. McMahon, J.J., P.A. Jones, and P. Comfort, *Standardisation of testing*, in *Performance Assessment in Strength and Conditioning*. 2018, Routledge. p. 34-41.
226. McMahon, J.J., J.P. Lake, and T.J. Suchomel, *Vertical jump testing*, in *Performance assessment in strength and conditioning*. 2018, Routledge. p. 96-116.

227. Los Arcos, A., et al., *Monitoring percieved respiratory and muscular exertions and physical fitness in young professional soccer players during a 32-week period.* Kinesiology, 2017. **49**: p. 153-160.

228. Naughton, M., et al., *Quantifying the collision dose in rugby league: A systematic review, meta-analysis, and critical analysis.* Sport Med, 2020. **6**(6).

229. Jarvis, P., et al., *Reactive Strength Index and its Associations with Measures of Physical and Sports Performance: A Systematic Review with Meta-Analysis.* Sports Med, 2021.

230. Moir, G.L., *Three Different Methods of Calculating Vertical Jump Height from Force Platform Data in Men and Women.* Measurement in Physical Education and Exercise Science, 2008. **12**(4): p. 207-218.

231. McBride, J.M., et al., *Relationship between relative net vertical impulse and jump height in jump squats performed to various squat depths and with various loads.* International journal of sports physiology and performance, 2010. **5**(4): p. 484-496.

232. Linthorne, N.P., *The correlation between jump height and mechanical power in a countermovement jump is artificially inflated.* Sports Biomech, 2021. **20**(1): p. 3-21.

233. Kennedy, R. and D. Drake, *The effect of acute fatigue on countermovement jump performance in rugby union players during preseason.* Journal of Sports Medicine and Physical Fitness, 2017. **57**(10): p. 1261-1266.

234. Tricco, A.C., et al., *PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation.* Annals of internal medicine, 2018. **169**(7): p. 467-473.

235. Peters, M.D., et al., *Best practice guidance and reporting items for the development of scoping review protocols.* JBI evidence synthesis, 2022. **20**(4): p. 953-968.

236. Peters, M.D., et al., *Updated methodological guidance for the conduct of scoping reviews.* JBI evidence implementation, 2021. **19**(1): p. 3-10.

237. Pollock, D., et al., *Methodological quality, guidance, and tools in scoping reviews: a scoping review protocol. JBI Evidence Synthesis, 20(4), pp.1098-1105.* 2022.

238. Kozinc, Ž., et al., *Effects of 12-week full body resistance exercise on vertical jumping with and without military equipment in Slovenian Armed Forces.* BMJ Mil Health, 2021.

239. Scanlan, A.T., et al., *The Commonality Between Approaches to Determine Jump Fatigue During Basketball Activity in Junior Players: In-Game Versus Across-Game Decrements.* International Journal of Sports Physiology & Performance, 2017. **12**(2): p. 260-263.

240. Troester, J.C. and R. Duffield, *Monitoring residual 36 h post-match neuromuscular fatigue in rugby union; a role for postural control?* European Journal of Sport Science, 2019. **19**(10): p. 1312-1319.

241. Travis, S.K., et al., *Preserving Isometric Maximal Strength Using Short-Term Training Cessation...2021 ACSM Annual Meeting & World Congresses [Virtual], June 1 -5, 2021.* Medicine & Science in Sports & Exercise, 2021. **53**: p. 40-41.

242. McLean, B.D., et al., *Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players.* International journal of sports physiology and performance, 2010. **5**(3): p. 367-383.

243. Roe, G., et al., *Changes in markers of fatigue following a competitive match in elite academy rugby union players.* South African Journal of Sports Medicine, 2016. **28**(1): p. 205.

244. Yu, P., et al., *The acute influence of running-induced fatigue on the performance and biomechanics of a countermovement jump.* Applied Sciences, 2020. **10**(12): p. 4319.

245. Silva, S., et al., *Methodological Considerations in the Kinematic and Kinetic Analysis of Human Movement among Healthy Adolescents, A Scoping Review of Nonlinear Measures in Data Processing.* Sensors, 2023. **23**(1): p. 304.

246. Pau, M., S. Kim, and M.A. Nussbaum, *Does load carriage differentially alter postural sway in overweight vs. normal-weight schoolchildren?* Gait & posture, 2012. **35**(3): p. 378-382.
247. McMahon, J.J., P. Comfort, and A. Turner, *Fitness testing and data analysis.*, in *Advanced Strength and Conditioning*, A. Turner and P. Comfort, Editors. 2017, Routledge. p. 190-202.
248. Owen, N.J., et al., *Development of a criterion method to determine peak mechanical power output in a countermovement jump.* The Journal of Strength & Conditioning Research, 2014. **28**(6): p. 1552-1558.
249. Street, G., et al., *Sources of error in determining countermovement jump height with the impulse method.* Journal of Applied Biomechanics, 2001. **17**(1): p. 43-54.
250. Logan, S., et al., *Ground reaction force differences between running shoes, racing flats, and distance spikes in runners.* Journal of Sports Science & Medicine, 2010. **9**(1): p. 147.
251. Hara, M., et al., *The effect of arm swing on lower extremities in vertical jumping.* Journal of biomechanics, 2006. **39**(13): p. 2503-2511.
252. Markovic, G., et al., *Reliability and factorial validity of squat and countermovement jump tests.* The Journal of Strength & Conditioning Research, 2004. **18**(3): p. 551-555.
253. Suchomel, T.J., *Current Issues and Future Research Directions in Sport Science: A Roundtable Discussion.* Strength & Conditioning Journal, 2022: p. 10-1519.
254. Kupperman, N. and J. Hertel, *Global positioning system–derived workload metrics and injury risk in team-based field sports: a systematic review.* Journal of athletic training, 2020. **55**(9): p. 931-943.
255. Pleša, J., Ž. Kozinc, and N. Šarabon, *A Brief Review of Selected Biomechanical Variables for Sport Performance Monitoring and Training Optimization.* Applied Mechanics, 2022. **3**(1): p. 144-159.
256. Haff, G.G., *Strength–isometric and dynamic testing*, in *Performance assessment in strength and conditioning*. 2018, Routledge. p. 166-192.
257. Hahn, D., *On the phase definitions of counter movement jumps.* Scandinavian Journal of Medicine & Science in Sports, 2023. **33**(3): p. 359-360.
258. Beckham, G., T. Suchomel, and S. Mizuguchi, *Force plate use in performance monitoring and sport science testing.* New Studies in Athletics, 2014. **29**(3): p. 25-37.
259. Harry, J.R., et al., *Low-pass filter effects on metrics of countermovement vertical jump performance.* Journal of strength and conditioning research, 2022. **36**(5): p. 1459-1467.
260. Hawkin Dynamics, I. *Hawkin Dynamics Metric Database*. 2023.
261. Hawkin Dynamics, I. *Hawkin Dynamics Information Packet*. 2021; Available from: https://www.hawkindynamics.com/hubfs/HawkinDynamics_InfoPacket2021_NewCloudv1.pdf.
262. Sole, C.J., et al., *Phase characteristics of the countermovement jump force-time curve: A comparison of athletes by jumping ability.* The Journal of Strength & Conditioning Research, 2018. **32**(4): p. 1155-1165.
263. Smith, J.C., H.S. Lamont, and M. Barefoot, *Comparison of Different Take-off Thresholds When Assessing Vertical Jump Performance.* International Journal of Exercise Science, 2024. **17**(1): p. 660.
264. McMahon, J.J., P.A. Jones, and P. Comfort, *Comparison of Countermovement Jump-Derived Reactive Strength Index Modified and Underpinning Force-Time Variables Between Super League and Championship Rugby League Players.* J Strength Cond Res, 2019.

265. Kibele, A., *Possibilities and limitations in the biomechanical analysis of countermovement jumps: A methodological study.* Journal of applied biomechanics, 1998. **14**(1): p. 105-117.
266. McMahon, J.J., et al., *RELATIONSHIP BETWEEN REACTIVE STRENGTH INDEX VARIANTS IN RUGBY LEAGUE PLAYERS.* Journal of Strength and Conditioning Research, 2021. **35**(1): p. 280-285.
267. Comfort, P., et al., *Effect of knee and trunk angle on kinetic variables during the isometric midthigh pull: Test–retest reliability.* International Journal of Sports Physiology and Performance, 2015. **10**(1): p. 58-63.
268. Dos'Santos, T., et al., *Effect of different onset thresholds on isometric midthigh pull force-time variables.* The Journal of Strength & Conditioning Research, 2017. **31**(12): p. 3463-3473.
269. Beckham, G.K., et al., *Effect of body position on force production during the isometric midthigh pull.* The Journal of Strength & Conditioning Research, 2018. **32**(1): p. 48-56.
270. Musham, C. and J.F. Fitzpatrick, *Familiarisation and reliability of the isometric mid-thigh pull in elite youth soccer players.* Sports Perf Sci Reports, 2020. **85**: p. 1-4.
271. Lake, J., et al., *The reliability and validity of the bar-mounted PUSH BandTM 2.0 during bench press with moderate and heavy loads.* Journal of Sports Sciences, 2019. **37**(23): p. 2685-2690.
272. Bland, J.M. and D. Altman, *Statistical methods for assessing agreement between two methods of clinical measurement.* The Lancet, 1986. **327**(8476): p. 307-310.
273. Ludbrook, J., *A primer for biomedical scientists on how to execute model II linear regression analysis.* Clin. Exp. Pharmacol. Physiol., 2012. **39**: p. 329-335.
274. Ludbrook, J., *Linear regression analysis for comparing two measurers or methods of measurement: but which regression?* Clin Exp Pharmacol Physiol, 2010. **37**(7): p. 692-9.
275. Ludbrook, J., *Confidence in Altman-Bland plots: a critical review of the method of differences.* Clin Exp Pharmacol Physiol, 2010. **37**(2): p. 143-9.
276. Mullineaux, D.R., C.A. Barnes, and A.M. Batterham, *Assessment of bias in comparing measurements: A reliability example.* Meas. Phys. Educ. Exerc. Sci., 1999. **3**: p. 195-205.
277. Ranganathan, P., C.S. Pramesh, and R. Aggarwal, *Common pitfalls in statistical analysis: Measures of agreement.* Perspect. Clin. Res., 2017. **8**: p. 187–191.
278. Ludbrook, J., *Multiple comparison procedures updated.* Clinical and Experimental Pharmacology and Physiology, 1998. **25**(12): p. 1032-1037.
279. Ludbrook, J., *Comparing methods of measurement.* Clinical and Experimental Pharmacology and Physiology, 1997. **24**(2): p. 198-203.
280. Crowder, G.E., et al., *The Validation of a Portable Dual-Force Plate System for Assessing Countermovement Jump Performance.*, in *American Society of Biomechanics*. 2020: Atlanta, GA.
281. Peterson Silveira, R., et al., *Validity of a portable force platform for assessing biomechanical parameters in three different tasks.* Sports biomechanics, 2017. **16**(2): p. 177-186.
282. Baca, N., *A comparison of methods for analyzing drop jump performance.* Medicine and science in sports and exercise, 1999. **31**(3): p. 437-442.
283. Cowling, E.J., J.R. Steele, and P.J. McNair, *Effect of verbal instructions on muscle activity and risk of injury to the anterior cruciate ligament during landing.* British journal of sports medicine, 2003. **37**(2): p. 126-130.
284. Starling, L.T., *Teams with lower injury rates have greater success in the Currie Cup rugby union competition.* South African journal of sports medicine, 2019. **31**(1): p. 1-2.

285. Carling, C., et al., *Squad management, injury and match performance in a professional soccer team over a championship-winning season.* European Journal of Sport Science, 2015. **15**(7): p. 573-582.
286. Young, W., B. McLean, and J. Ardagna, *Relationship between strength qualities and sprinting performance.* Journal of sports medicine and physical fitness, 1995. **35**(1): p. 13-19.
287. Mason, L., et al., *The relationship between isometric mid-thigh pull variables and athletic performance measures: Empirical study of English professional soccer players and meta-analysis of extant literature.* Journal of Sports Medicine and Physical Fitness, 2021. **61**(5): p. 645-655.
288. McMahon, J.J., et al., *Vertical Jump Testing in Rugby League: A Rationale for Calculating Take-Off Momentum.* J Appl Biomech, 2020: p. 1-5.
289. Weldon, A., et al., *Practices of strength and conditioning coaches in professional sports: a systematic review.* Biology of Sport, 2021. **39**(3): p. 715-726.
290. McMahon, J.J., et al., *Understanding the key phases of the countermovement jump force-time curve.* Strength and Conditioning Journal, 2018. **40**(4): p. 96-106.
291. Kennedy, R.A. and D. Drake, *Improving the signal-to-noise ratio when monitoring countermovement jump performance.* The Journal of Strength & Conditioning Research, 2021. **35**(1): p. 85-90.
292. Ruf, L., et al., *Poor Reliability of Measurement Instruments to Assess Acute Responses to Load in Soccer Players Irrespective of Biological Maturity Status.* Pediatric Exercise Science, 2022. **34**(3): p. 125-134.
293. Anicic, Z., et al., *Assessment of Countermovement Jump: What Should We Report?* Life, 2023. **13**(1): p. 190.
294. Cormack, S.J., et al., *Reliability of Measures Obtained During Single and Repeated Countermovement Jumps.* International Journal of Sports Physiology and Performance, 2008. **3**(2): p. 131-144.
295. Claudino, J.G., et al., *The countermovement jump to monitor neuromuscular status: A meta-analysis.* Journal of science and medicine in sport, 2017. **20**(4): p. 397-402.
296. McMahon, J.J., J.P. Lake, and P. Comfort, *Identifying and reporting position-specific countermovement jump outcome and phase characteristics within rugby league.* PloS one, 2022. **17**(3): p. p.e0265999.
297. Koo, T.K. and M.Y. Li, *A guideline of selecting and reporting intraclass correlation coefficients for reliability research.* Journal of chiropractic medicine, 2016. **15**(2): p. 155-163.
298. Arifin, W.N. *Sample size calculator (web).* 2024; Available from: Retrieved from http://wnarifin.github.io.
299. Bonett, D.G., *Sample size requirements for estimating intraclass correlations with desired precision.* Statistics in medicine, 2002. **21**(9): p. 1331-1335.
300. Borg, D.N., et al., *Calculating sample size for reliability studies.* PM&R, 2022. **14**(8): p. 1018-1025.
301. Walter, S.D., M. Eliasziw, and A. Donner, *Sample size and optimal designs for reliability studies.* Statistics in medicine, 1998. **17**: p. 101-110.
302. McKay, A.K.A., et al., *Defining Training and Performance Caliber: A Participant Classification Framework.* International Journal of Sports Physiology and Performance, 2022. **17**(2): p. 317-331.
303. Bland, J.M. and D.G. Altman, *Measurement error.* British medical journal, 1996. **312**(7047): p. 1654.
304. Altman, D.G. and J.M. Bland, *Standard deviations and standard errors.* British Medical Journal, 2005. **331**(7521): p. 903.

305. Declerck, L., et al., *Standard error of measurement and minimal detectable change of the French physical activity scale for individuals with physical disabilities.* Annals of physical and rehabilitation medicine., 2022. **65**(3): p. 101583.
306. Terwee, C.B., et al., *Minimal important change (MIC): a conceptual clarification and systematic review of MIC estimates of PROMIS measures.* Quality of life Research, 2021. **30**: p. 2729-2754.
307. Bland, J.M. and D.G. Altman, *Measurement error proportional to the mean.* British Medical Journal, 1996. **313**(7049): p. 106.
308. Banyard, H.G., K. Nosaka, and G.G. Haff, *Reliability and validity of the load–velocity relationship to predict the 1RM back squat.* The Journal of Strength & Conditioning Research, 2017. **31**(7): p. 1897-1904.
309. Cortina, J.M., *What is coefficient alpha? An examination of theory and applications.* Journal of applied psychology, 1993. **78**(1): p. 98.
310. Pérez-Castilla, A., et al., *Reliability and magnitude of countermovement jump performance variables: Influence of the take-off threshold.* Measurement in Physical Education and Exercise Science, 2021. **25**(3): p. 227-235.
311. Claudino, J.G., et al., *The countermovement jump to monitor neuromuscular status: A meta-analysis.* Journal of science and medicine in sport, 2017. **20**(4): p. 397-402.
312. Markström, J.L. and C.J. Olsson, *Countermovement jump peak force relative to body weight and jump height as predictors for sprint running performances (in) homogeneity of track and field athletes?* The Journal of Strength & Conditioning Research, 2013. **27**(4): p. 944-953.
313. Merrigan, J.J., et al., *Identifying reliable and relatable force–time metrics in athletes. Considerations for the isometric mid-thigh pull and countermovement jump.* Sports, 2020. **9**(1): p. 4.
314. Harry, J.R., et al., *Relationships among countermovement vertical jump performance metrics, strategy variables, and inter-limb asymmetry in females.* Sports biomechanics, 2021: p. 1-19.
315. Jalilvand, F., et al., *Relationship between body mass, peak power, and power-to-body mass ratio on sprint velocity and momentum in high-school football players.* The Journal of Strength & Conditioning Research, 2019. **33**(7): p. 1871-1877.
316. Suchomel, T.J., C.J. Sole, and M.H. Stone, *COMPARISON OF METHODS THAT ASSESS LOWER-BODY STRETCH-SHORTENING CYCLE UTILIZATION.* Journal of Strength & Conditioning Research (Lippincott Williams & Wilkins), 2016. **30**(2): p. 547-554.
317. Moir, G.L., A. Garcia, and G.B. Dwyer, *Intersession Reliability of Kinematic and Kinetic Variables During Vertical Jumps in Men and Women.* International Journal of Sports Physiology and Performance, 2009. **4**(3): p. 317-330.
318. Kelley, K. and J.R. Rausch, *Sample size planning for the standardized mean difference: accuracy in parameter estimation via narrow confidence intervals.* Psychological methods, 2006. **11**(4): p. 363.
319. Faul, F., et al., *Statistical power analyses using G* Power 3.1: Tests for correlation and regression analyses.* Behavior research methods, 2009. **41**(4): p. 1149-1160.
320. Faul, F., et al., *G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences.* Behavior research methods, 2007. **39**(2): p. 175-191.
321. Mann, H.B. and D.R. Whitney, *On a test of whether one of two random variables is stochastically larger than the other.* The annals of mathematical statistics., 1947: p. 50-60.

322. Baker, D. and R. Newton, *Comparison of Lower Body Strength, Power, Acceleration, Speed, Agility, and Sprint Momentum to Describe and Compare Playing Rank among Professional Rugby League Players.* The Journal of Strength & Conditioning Research. 2008; 22:153., 2008. **22**(153).
323. Ebben, W.P. and E.J. Petushek, *Using the reactive strength index modified to evaluate plyometric performance.* The Journal of Strength & Conditioning Research, 2010. **24**(8): p. 1983-1987.
324. Flanagan, E.P. and T.M. Comyns, *The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training.* Strength & Conditioning Journal, 2008. **30**(5): p. 32-38.
325. Kennedy, R.A. and D. Drake, *Is a Bimodal Force-Time Curve Related to Countermovement Jump Performance?* Sports (Basel), 2018. **6**(2).
326. Heishman, A., et al., *The Influence of Countermovement Jump Protocol on Reactive Strength Index Modified and Flight Time: Contraction Time in Collegiate Basketball Players.* Sports (Basel), 2019. **7**(2).
327. Douglas, J., et al., *Kinetic Determinants of Reactive Strength in Highly Trained Sprint Athletes.* J Strength Cond Res, 2018. **32**(6): p. 1562-1570.
328. Barker, L.A., J.R. Harry, and J.A. Mercer, *Relationships Between Countermovement Jump Ground Reaction Forces and Jump Height, Reactive Strength Index, and Jump Time.* J Strength Cond Res, 2018. **32**(1): p. 248-254.
329. Sole, C.J., T.J. Suchomel, and M.H. Stone, *Preliminary Scale of Reference Values for Evaluating Reactive Strength Index-Modified in Male and Female NCAA Division I Athletes.* Sports (Basel), 2018. **6**(4).
330. Rossi, S.J., J. McMillan, and T. Buckley, *Seasonal Changes of Drop Jump Performance and Recovery-Stres Scores in Collegiate Soccer Players. [Abstract]*. Journal of Strength & Conditioning Research March 2011;25 Supplement 1:S106.
331. Pérez-Castilla, A., et al., *Influence of countermovement depth on the countermovement jump-derived reactive strength index modified.* Eur J Sport Sci, 2020: p. 1-11.
332. Turner, A., *Training for power: Principles and practice.* Professional Strength & Conditioning., 2009.
333. Baker, D., *The effects of an in-season of concurrent training on the maintenance of maximal strength and power in professional and college-aged rugby league football players.* The Journal of Strength & Conditioning Research, 2001. **15**(2): p. 172-177.
334. Baker, D. and R.U. Newton, *Methods to increase the effectiveness of maximal power training for the upper body.* Strength & Conditioning Journal, 2005. **27**(6): p. 24-32.
335. Nuzzo, J.L., et al., *Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength.* The Journal of Strength & Conditioning Research, 2008. **22**(3): p. 699-707.
336. Peterson, M.D., B.A. Alvar, and M.R. Rhea, *The contribution of maximal force production to explosive movement among young collegiate athletes.* The Journal of Strength & Conditioning Research, 2006. **20**(4): p. 867-873.
337. García-Aliaga, A., et al., *A longitudinal study on the evolution of the four main football leagues using artificial intelligence: analysis of the differences in English Premier League teams.* Research Quarterly for Exercise and Sport, 2023. **94**(2): p. 529-537.
338. Thorpe, R.T., *Post-exercise recovery: cooling and heating, a periodized approach.* Frontiers in Sports and Active Living, 2021. **3**: p. 707503.
339. Owen, A., et al., *The relationship between lower-limb strength and match-related muscle damage in elite level professional European soccer players.* Journal of sports sciences, 2015. **33**(20): p. 2100-2105.

340. Jeffreys, I., *Warm up revisited–the 'ramp'method of optimising performance preparation.* UKSCA Journal, 2006. **6**: p. 15-19.
341. Crang, Z.L., et al., *The validity of raw custom-processed global navigation satellite systems data during straight-line sprinting across multiple days.* . Journal of Science and Medicine in Sport., 2023.
342. Waqar, A., et al., *Analysis of GPS and UWB positioning system for athlete tracking.* Measurement: Sensors, 2021. **14**: p. 100036.
343. *The jamovi project. Jamovi (Version 2.3) [Computer Software]. Retrieved from* https://www.jamovi.org. 2023.
344. Armstrong, R.A., *When to use the Bonferroni correction.* Ophthalmic and Physiological Optics, 2014. **34**(5): p. 502-508.
345. Dunn, O.J., *Multiple comparisons among means.* Journal of the American statistical association, 1961. **56**(293): p. 52-64.
346. Olejnik, S., et al., *Multiple testing and statistical power with modified Bonferroni procedures.* Journal of educational and behavioral statistics, 1997. **22**(4): p. 389-406.
347. Bland, J.M. and D.G. Altman, *Multiple significance tests: the Bonferroni method.* Bmj, 1995. **310**: p. 170.
348. Fraenkel, J., N. Wallen, and H. Hyun, *How to Design and Evaluate Research in Education.* 2011.
349. Hecksteden, A., R. Kellner, and L. Donath, *Dealing with small samples in football research.* Science and medicine in football, 2022. **6**(3): p. 389-397.
350. Owen, N.J., et al., *Development of a Criterion Method to Determine Peak Mechanical Power Output in a Countermovement Jump.* The Journal of Strength & Conditioning Research, 2014. **28**(6): p. 1552-1558.

12 APPENDICES

12.1 Abstract Submission to ISBS Conference (Liverpool 2022)

AGREEMENT AMONG COUNTERMOVEMENT JUMP FORCE-TIME VARIABLES OBTAINED FROM A WIRELESS DUAL FORCE PLATE SYSTEM AND AN INDUSTRY GOLD STANDARD SYSTEM

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The purpose of this study was to explore the agreement between a wireless and portable dual force plate system, and an in-ground force plate system, which is an industry gold standard. The countermovement jump (CMJ) was compared across the two systems because it is the most popular force plate test in sports settings. Recreationally active adults (*n*=20) performed three maximal-effort CMJs on the portable force plates which were placed atop two adjacent in-ground force plates to enable simultaneous collection of raw force-time data (1000 Hz) over five seconds. Popular CMJ force-time variables were analysed for each system using a custom Microsoft Excel spreadsheet using criterion methods. Ordinary least products regression (OLPR) showed no fixed or proportional bias between the force plate systems for all variables. Thus, the portable force plate system may be considered a valid alternative to an industry gold standard for the assessment of CMJ force-time variables.

KEYWORDS: Neuromuscular function, physical performance testing, concurrent validity.

INTRODUCTION: Neuromuscular function (NMF) is commonly evaluated utilising biomechanical apparatus such as force plates, which enable the collection of force-time data. Appropriate software (e.g., proprietary software or Microsoft Excel) can then be used to produce force-time curves and, in vertical jump tasks, forward dynamics can be applied to calculate a multitude of performance variables relating to acceleration, velocity, and displacement [25]. Practitioners utilise force-time data to objectify physical capacities, evaluate athlete's neuromuscular response to training and match play stimuli, and ultimately highlight individual and team physical preparedness.

The advent of commercially available, portable, and affordable hardware and software, which produces immediately available reports, means there is a new opportunity to gain more informative data on NMF, more easily, and in situations where this was not previously possible. These data can be used immediately to inform players, coaches, and medical staff on individual preparedness to train and compete, and recommended prescription [25]. However, with the increased practicality of systems, accuracy must be maintained, as this is the main factor in determining an appropriate evaluation device [271]. To establish system accuracy, uncovering any systematic disagreement between said apparatus and a widely used and thoroughly investigated "gold standard" system using appropriate agreement statistics is critical [273, 279]. A recently emerging system, which is gaining popularity within high performance, occupational, and medical contexts is a portable, wireless, dual force plate system by HD Inc. A single study has looked to establish the concurrent validity of the HD Inc. force plate system, however, with limited statistical analyses (e.g., Pearson correlation coefficients and LOA), and CMJ (a common test of NMF) outcome variables alone [280].

In this study, we aimed to determine the concurrent validity of the HD Inc. force plate system by assessing agreement between select variables derived from the force-time data (herein defined as "force-time variables") during the CMJ task to those derived from a laboratory grade, in-ground force plate system (i.e., a "gold standard"). The results of this study will inform the efficacy of using the HD Inc. force plate system in future research projects, and in applied sports settings.

METHODS: Twenty recreationally active adults (age = 27 ± 6 years, body mass = 85 ± 14 kg) with a varied sports background and who were injury free volunteered to participate. Current training status and previous resistance and CMJ training experience were not a limiting factor in this study, due to its focus on agreement between the two force plate systems alone. Informed consent was provided, and the study was pre-approved by the Institutional Ethics Committee before recruitment and testing commenced.

A cross-sectional design was employed, whereby testing was conducted during a single session within a human performance laboratory. A standardised warm-up (~ 10 mins) consisting of dynamic stretching and submaximal CMJs was performed by each participant prior to testing to reduce the risk of injury. The HD Inc. force plate system (Westbrook, Maine, USA) consisting of 2 force plates was placed directly on top of two adjacent in-ground force plates (Advanced Medical Technology Inc., [AMTI], Massachusetts, USA) to collect forces produced through each leg independently and simultaneously. The vertical component of the raw vertical GRF data was collected at 1000 Hz over five seconds via HD Inc. proprietary software and Qualisys Track Manager software (Qualisys Ltd., Gothenburg, Sweden) for the HD Inc. and AMTI systems, respectively. Both systems were zeroed before each CMJ trial. Participants then stepped onto the force plates, stood completely upright (extended hips and knees) and motionless for at least one second before completing a maximal effort CMJ following a "3, 2, 1, jump" command. Participants were cued to jump "as fast and high as possible" for three recorded CMJ trials with arms akimbo.

The raw vertical GRF data was exported from each system's software to Microsoft Excel, which was used to analyse the bilateral forces (summed left and right leg forces) using a custom spreadsheet. The average across three CMJ trials (for each variable) was taken forward for statistical analyses. The participants' body weight was calculated by averaging the vertical force trace over the first one second of data collection when the subject was stationary on the force plate [230]. Onset of movement was identified as 30 ms prior to the instant when vertical force is reduced by a threshold equal to 5 times the SD of BW (calculated in the weighing phase) [350]. To identify take-off and touchdown, a threshold of force equal to 5 times the SD of flight force (when the force platform is unloaded), taken over a 300-ms portion of the flight phase, was used (McMahon et al., 2018). Time to take-off was calculated as the time between the onset of movement and take-off. Due to the AMTI system having greater flight phase force (~16 N vs ~ 8 N), we used the AMTI take-off threshold for both systems. The CMJ phases were identified using the terminology explained recently [25]. Braking and propulsion peak force, mean force, and net impulse, were defined as explained in previous research [165]. Countermovement depth was taken from the onset of movement to the end of the braking phase. Peak propulsive velocity and TOV were determined based on impulse-momentum theorem. JH was derived from the TOV method [230]. The modified reactive strength index (mRSI) was calculated as JH divided by time to take-off [165].

Statistical analyses were performed using SPSS software (version 25; SPSS Inc., Chicago, IL, USA). The potential sources of systematic disagreement between force plate systems were determined via OLPR, which was conducted following the recommendations of Ludbrook [273, 279]. If the bootstrapped 95% confidence interval (CI) for the intercept did not include 0, then fixed bias was inferred to be present. If the bootstrapped 95% CI for the slope did not include 1, then proportional bias was inferred to be present.

RESULTS: The OLPR coefficients and corresponding bootstrapped 95% CIs are reported in Table 1. For all variables investigated, one can infer there was no fixed or proportional bias between the two force plate systems. Therefore, it may be suggested that the wireless dual force plate system may be considered a valid alternative to the industry gold standard with respect to measuring common CMJ force-time variables.

Table 1. Descriptive and agreement statistics for the selected variables.

	AMTI (Mean ± SD)			Hawkin Dynamics (Mean ± SD)				Slope *95% CI*			Intercept *95% CI*	
mRSI (ratio)	0.43	±	0.10	0.43	±	0.10		1.013			-0.004	
							0.991	*to*	*1.036*	*-0.012*	*to*	*0.004*
Jump Height (m)	0.31	±	0.07	0.31	±	0.06		1.030			-0.005	
							0.978	*to*	*1.082*	*-0.020*	*to*	*0.010*
Time to Takeoff (s)	0.763	±	0.089	0.768	±	0.088		1.006			-0.013	
							0.956	*to*	*1.036*	*-0.057*	*to*	*0.004*
Peak Velocity (m/s)	2.6	±	0.3	2.6	±	0.2		1.033			-0.074	
							0.989	*to*	*1.077*	*-0.186*	*to*	*0.038*
Propulsive Net Impulse (Ns)	210	±	42	209	±	42		0.992			2.789	
							0.974	*to*	*1.010*	*-1.043*	*to*	*6.622*
Avg. Propulsive Force (N)	1668	±	292	1664	±	291		1.003			-2.258	
							0.997	*to*	*1.010*	*-12.429*	*to*	*7.912*
Peak Propulsive Force (N)	2043	±	344	2041	±	344		0.999			3.921	
							0.995	*to*	*1.003*	*-5.245*	*to*	*13.088*
Countermovement depth (m)	-0.30	±	0.06	-0.30	±	0.06		1.014			0.007	
							0.971	*to*	*1.058*	*-0.006*	*to*	*0.020*
Braking Net Impulse (Ns)	107	±	25	107	±	25		1.004			-0.907	
							0.991	*to*	*1.016*	*-2.073*	*to*	*0.259*
Avg. Braking Force (N)	1496	±	251	1498	±	251		0.999			-1.584	
							0.993	*to*	*1.005*	*-10.655*	*to*	*7.487*
Peak Braking Force (N)	1952	±	320	1953	±	320		0.998			2.526	
							0.991	*to*	*1.005*	*-11.804*	*to*	*16.856*
Body Weight (N)	833	±	142	834	±	142		1.002			-1.881	
							0.995	*to*	*1.009*	*-7.795*	*to*	*4.032*

Key: SD, standard deviation; CI, confidence interval; m, metres; s, seconds; N, Newtons; Avg, Average.

DISCUSSION: The purpose of this study was to determine the concurrent validity of a wireless and fully portable dual force plate system by HD Inc. by assessing agreement between select force-time variables during the CMJ task to those derived from an AMTI system, considered a "gold standard". The wireless dual force plate system can be considered a valid alternative to the criterion, industry gold standard with respect to collecting CMJ force-time data, because the OLPR analysis showed no fixed or proportional bias between the two force plate systems for any of the variables (Table 1).

Although the present findings support the conclusions of the sole previous study with a similar approach [280], the results here indicate a better agreement between the two force plate systems. This is due to this study performing what may be considered a philosophically more robust methodological and statistical approach design. For example, in the study by Crowder et al. [280], it is unclear whether their participants performed three maximal effort CMJs on the HD Inc. and AMTI systems, separately. This is an initial concern, as it is rare that participants will perform separate CMJ trials with identical force-time variables. This introduces random error due to inherent biological variation, which confounds the mechanical variation we are investigating. Additionally, the previous study only assessed the mean bias between systems for the outcome JH alone without assessing agreement between the strategy metrics underpinning JH. In contrast, the present study performed a more thorough analysis by including CMJ strategy variables. From a statistical perspective, the more philosophically robust OLPR analysis was chosen in this study, according to recommendations from Ludbrook [273, 279], as opposed to the lesser regarded Pearson's Correlation Coefficients, and Bland-Altman plots with 95% LOA used by Crowder et al. [280]. Differences in data collection frequencies were also evident, with the AMTI system collecting at 1200Hz, whereas the HD Inc. system collected at 1000 Hz [280]. This discrepancy can affect key events of the CMJ, such as onset of movement and take-off thresholds. Additionally, they allowed participants to use AS during trials, which adds another factor which can affect the variability of trials. The researchers highlighted that the inclusion of AS could have increased the variability of trials, as has been seen in previous research, and thus the pattern of mean difference seen between systems [280]. Taken together, the methodological shortcomings of the Crowder et al. [280] study may explain why their LOA analysis showed that JH collected with the HD Inc. system could be expected to range anywhere from 7.10 cm lower to 7.63 cm higher than that measured by the AMTI system, which we deem unacceptable.

Based on the present study, practitioners can consider the HD Inc. system as an accurate system to use as an alternative to the traditional, non-portable and more expensive in-ground AMTI system. This is useful information for practitioners seeking a system to evaluate NMF using CMJs in sports, but are restricted by system complexity, location, and price. Due to the increased practicality of the HD Inc. system, this can now be done easily in competition and training environments previously unavailable to practitioners. For example, the system can be used at any training facility to monitor NMF capacity, as a training tool in the gym to increase within-session intent and monitor between-session progress, and pitch- or trackside after sessions to determine the neuromuscular response to training or competition. These factors also apply to researchers who can now ask and answer more authentic research questions relating to neuromuscular fitness and fatigue in sports settings.

As this study has found agreement in the commonly used CMJ assessment, further research should consider identifying these patterns with different vertical jump tasks. Exploring agreement between these systems for jumps that involve different magnitudes, rates, and frequencies of loading (e.g., repeated peak landing forces in rebound jumps) would be worthwhile. Additionally, the strain gauge-based HD Inc. force plate system may also be compared to other portable force plate systems, including those that use piezoelectric sensors. Finally, replicating this study with athletes who can obtain extreme jump heights would be efficacious.

CONCLUSION: The results of this study demonstrate that there is no fixed or proportional bias between the HD Inc. and AMTI (gold standard) force plate systems for measuring common CMJ strategy and outcome variables. Therefore, this wireless and fully portable dual force plate system may be considered a valid alternative to the industry gold standard for the assessment of CMJ force-time variables and thus may be confidently used for this purpose by researchers and practitioners alike who currently (or plan to) use the HD Inc. force plate system.

ABSTRACT REFERENCES

Crowder, G. E., Pexa, B. S., Ford, K. R., & Waxman, J. P. (2020). The Validation of a Portable Dual-Force Plate System for Assessing Countermovement Jump Performance. American Society of Biomechanics, Atlanta, GA.

Lake, J., Augustus, S., Austin, K., Comfort, P., McMahon, J. J., Mundy, P., & Haff, G. G. (2019). The reliability and validity of the bar-mounted PUSH BandTM 2.0 during bench press with moderate and heavy loads. Journal of Sports Sciences, 37(23), 2685-2690.

Ludbrook, J. (1997). Comparing methods of measurement. Clinical and Experimental Pharmacology and Physiology, 24(2), 198-203.

Ludbrook, J. (2012). A primer for biomedical scientists on how to execute model II linear regression analysis. Clin. Exp. Pharmacol. Physiol., 39, 329-335.

McMahon, J. J., Jones, P. A., & Comfort, P. (2022). Comparison of Countermovement Jump-Derived Reactive Strength Index Modified and Underpinning Force-Time Variables Between Super League and Championship Rugby League Players. J Strength Cond Res, 36(1), 226-231.

McMahon, J. J., Suchomel, T. J., Lake, J. P., & Comfort, P. (2018). Understanding the key phases of the countermovement jump force-time curve. Strength and Conditioning Journal, 40(4), 96-106.

Moir, G. L. (2008). Three Different Methods of Calculating Vertical Jump Height from Force Platform Data in Men and Women. Measurement in Physical Education and Exercise Science, 12(4), 207-218.

Owen, N. J., Watkins, J., Kilduff, L. P., Bevan, H. R., & Bennett, M. A. (2014). Development of a Criterion Method to Determine Peak Mechanical Power Output in a Countermovement Jump. The Journal of Strength & Conditioning Research, 28(6), 1552-1558.

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AGREEMENT AMONG COUNTERMOVEMENT JUMP FORCE-TIME VARIABLES OBTAINED FROM A WIRELESS DUAL FORCE PLATE SYSTEM AND AN INDUSTRY GOLD STANDARD SYSTEM

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INTRODUCTION

The purpose of this study was to explore the agreement in countermovement jump (CMJ) force-time metrics between a wireless and portable dual force plate system (Hawkin Dynamics Inc., [HD], Maine, USA), and an in-ground force plate system, which is an industry gold standard (Advanced Mechanical Technology Inc., [AMTI], Massachusetts, USA).

METHODS

Recreationally active adults (n = 20, age = 27 ± 6 years, body mass = 85 ± 14 kg) performed three maximal-effort CMJs on the HD force plates which were placed atop two adjacent, in-ground, AMTI force plates to enable the simultaneous collection of raw vertical ground reaction force-time data (1000 Hz). This data was then exported from each system's software to Microsoft Excel, which was used to analyse the bilateral forces (summed left and right leg forces) using a custom spreadsheet. Numerous jump strategy and outcome variables were selected and the average of across three CMJ trials (for each variable) was taken forward for statistical analyses. Statistical agreement between force plate systems were determined via ordinary least products regression (OLPR), which was conducted following the recommendations of Ludbrook (1997, 2012). If the bootstrapped 95% confidence interval (CI) for the intercept did not include 0, then fixed bias was inferred to be present. If the bootstrapped 95% CI for the slope did not include 1, then proportional bias was inferred to be present.

RESULTS

Table 1. Descriptive and agreement statistics for the selected variables.

Metric	AMTI (Mean ± SD)	Hawkin Dynamics (Mean ± SD)	Slope 95% CI	Intercept 95% CI
mRSI (ratio)	0.43 ± 0.10	0.43 ± 0.10	1.013 *0.991 to 1.036*	-0.004 *-0.012 to 0.004*
Jump Height (m)	0.31 ± 0.07	0.31 ± 0.06	1.030 *0.978 to 1.082*	-0.005 *-0.020 to 0.010*
Time to Takeoff (s)	0.763 ± 0.089	0.768 ± 0.088	1.006 *0.956 to 1.036*	-0.013 *-0.057 to 0.004*
Peak Velocity (m/s)	2.6 ± 0.3	2.6 ± 0.2	1.033 *0.989 to 1.077*	-0.074 *-0.186 to 0.038*
Propulsive Net Impulse (Ns)	210 ± 42	209 ± 42	0.992 *0.974 to 1.010*	2.789 *-1.043 to 6.622*
Avg. Propulsive Force (N)	1668 ± 292	1664 ± 291	1.003 *0.997 to 1.010*	-2.258 *-12.429 to 7.912*
Peak Propulsive Force (N)	2043 ± 344	2041 ± 344	0.999 *0.995 to 1.003*	3.921 *-5.245 to 13.088*
Countermovement depth (m)	-0.30 ± 0.06	-0.30 ± 0.06	1.014 *0.971 to 1.058*	0.007 *-0.006 to 0.020*
Braking Net Impulse (Ns)	107 ± 25	107 ± 25	1.004 *0.991 to 1.016*	-0.907 *-2.073 to 0.259*
Avg. Braking Force (N)	1496 ± 251	1498 ± 251	0.999 *0.993 to 1.005*	-1.584 *-10.655 to 7.487*
Peak Braking Force (N)	1952 ± 320	1953 ± 320	0.998 *0.991 to 1.005*	2.526 *-11.804 to 16.856*
Body Weight (N)	833 ± 142	834 ± 142	1.002 *0.995 to 1.009*	-1.881 *-7.795 to 4.032*

Key: mRSI, modified reactive strength index; SD, standard deviation; CI, confidence interval; m, metres; s, seconds; N, Newtons; Avg, Average.

The OLPR coefficients and corresponding bootstrapped 95% CIs are reported in Table 1. There was no fixed or proportional bias between the two force plate systems.

DISCUSSION

The wireless dual force plate system can be considered a valid alternative to the criterion, industry gold standard with respect to collecting CMJ force-time data, because the OLPR analysis showed no fixed or proportional bias between the two force plate systems for any of the variables (Table 1).

This is useful information for practitioners seeking a system to evaluate neuromuscular function (NMF) using CMJs in sports, but are restricted by system complexity, location, and price. Due to the practicality of the HD system, this facilitates accurate testing to be done easily in competition and training environments. For example, the system can be used at any training facility to monitor NMF capacity, as a training tool in the gym to increase within- session intent and monitor between-session progress, and pitch- or trackside after sessions to determine the neuromuscular response to training or competition. These factors also apply to researchers who aim to ask and answer authentic research questions relating to neuromuscular fitness and fatigue in sports settings.

As this study has found agreement in the selected variables in the commonly used CMJ assessment, further research should consider identifying these patterns with different vertical jump tasks. Exploring agreement between these systems for jumps that involve different magnitudes, rates, and frequencies of loading (e.g., repeated peak landing forces in rebound jumps) would be worthwhile. Additionally, the strain gauge-based HD force plate system may also be compared to other portable force plate systems, including those that use piezoelectric sensors. Finally, replicating this study with athletes who can obtain extreme jump heights would be efficacious.

CONCLUSION

The results of this study demonstrate that there is no fixed or proportional bias between the HD and AMTI (gold standard) force plate systems for measuring common CMJ strategy and outcome variables. Therefore, this wireless and fully portable dual force plate system may be considered a valid alternative to the industry gold standard for the assessment of CMJ force-time variables and thus may be confidently used for this purpose by researchers and practitioners alike who currently (or plan to) use the HD force plate system.

REFERENCES

Ludbrook, J. (1997). Comparing methods of measurement. Clinical and Experimental Pharmacology and Physiology, 24(2), 198-203.
Ludbrook, J. (2012). A primer for biomedical scientists on how to execute model II linear regression analysis. Clinical and Experimental Pharmacology and Physiology, 39, 329-335.

12.3 Abstract Submission to NSCA Conference (New Orleans 2022)

BETWEEN-SESSION RELIABILITY OF THE COUNTERMOVEMENT JUMP AND COUNTERMOVEMENT REBOUND JUMP TESTS IN YOUTH SOCCER PLAYERS.

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Short Title: COUNTERMOVEMENT JUMP AND COUNTERMOVEMENT REBOUND JUMP TESTS BETWEEN-SESSION RELIABILITY.

The countermovement jump (CMJ) is commonly administered in soccer as a test of neuromuscular function during a “slow” (i.e., >250 ms movement time) stretch-shortening cycle (SSC) task. In contrast, the countermovement rebound jump (CMRJ) has been proposed as a test to assess “fast” SSC capacity (i.e., <250 ms contact time), however, the reliability of the CMRJ has yet to be reported. **PURPOSE:** The aim of this study was to quantify the between-session reliability of selected force plate metrics obtained during the CMJ (as a reference vertical jump test) and CMRJ test in youth soccer players. **METHODS:** Forty-three male youth soccer players (age 17.9 ± 0.9 years, height 181 ± 5.8 cm, body mass 72.5 ± 6.8 kg) performed three CMJs and three CMRJs, in a randomized order, on two separate occasions (seven days apart), during the in-season period. Vertical ground reaction forces (vGRFs) were acquired using two separate wireless dual force plate systems (HD Inc.) capturing at 1000 Hz. Athletes stood still for the initial 1 s of both tests to enable the calculation of body weight. Athletes performed all trials with arms akimbo and jumped “as fast and high as possible”. The vGRFs were low pass filtered (50 Hz) and analyzed using criterion methods via Hawkin Dynamics, Inc. proprietary software. Several key jump strategy and outcome variables were reported. Absolute reliability was assessed by CV, expressed as a percentage (with ≤5% considered excellent and 5.1-10% considered good). Relative reliability was assessed by a two-way mixed-effects model (average measures) intraclass correlation coefficient (ICC, with 0.75-0.89 considered good and ≥0.9 considered excellent). Upper and lower 95% confidence intervals for the CVs and ICCs, respectively, were calculated to help generalize the reliability scores. **RESULTS:** All variables calculated for the CMJ and CMRJ demonstrated good to excellent relative reliability (ICC >0.75). All variables calculated for the CMJ and CMJ portion

of the CMRJ showed good to excellent absolute reliability (1-10%). Absolute reliability was poorest for reactive strength index (RSI) (14%), contact time (13%) and braking depth (20%) recorded for the rebound jump (RJ) portion of the CMRJ compared with all other variables which showed good-excellent CV values (3-9%) (Table 1). **CONCLUSIONS:** Most CMJ and CMRJ variables are reliable for male youth soccer players. The greater between-session variability in RJ braking depth, contact time and RSI reveals some inconsistencies in RJ strategy. The variable RJ strategy was not considered to be due to changes in the preceding jump height from the CMJ phase of the CMRJ, as this showed low variability (6%). **PRACTICAL APPLICATIONS:** The CMRJ shows promise as a test of fast SSC ability in youth soccer players but more familiarity with the test is likely needed to further reduce between-session variability and thus increase the sensitivity of this test to change.

Table 1. Absolute and Relative Reliability of the Countermovement Jump and Countermovement Rebound Jump Tests.

	Mean Difference	CV%	CV% +95	ICC	ICC -95
CMRJ (RJ Portion)					
RSI (ratio)	0.09	14.0	27.5	0.87	0.76
Jump Height (m)	0.00	7.2	14.1	0.88	0.77
Jump Momentum (kg.m/s)	1.0	3.5	6.9	0.94	0.89
Takeoff Velocity (m/s)	0.03	4.8	9.4	0.81	0.66
Ground Contact Time (s)	0.02	13.0	25.5	0.87	0.71
Avg. Propulsive Force (N)	96	6.8	13.4	0.90	0.79
Peak Propulsive Force (N)	166	9.3	18.2	0.93	0.87
Braking Depth (m)	0.02	20.2	39.6	0.88	0.74
Braking Net Impulse (Ns)	3.0	3.1	6.1	0.95	0.90
Avg. Braking Force (N)	87.7	7.9	15.5	0.91	0.83
Peak Braking Force (N)	155.3	9.1	17.7	0.93	0.86
CMRJ (CMJ Portion)					
mRSI (ratio)	0.01	7.4	14.6	0.93	0.88
Jump Height (m)	0.01	5.6	10.9	0.87	0.75
Jump Momentum (kg.m/s)	2.3	2.9	5.7	0.95	0.91
Takeoff Velocity (m/s)	0.05	4.3	8.3	0.75	0.54
Time to Take-off (s)	0.02	8.1	15.8	0.83	0.69
Avg. Propulsive Force (N)	36.4	3.8	7.5	0.96	0.92
Peak Propulsive Force (N)	76.1	6.2	12.1	0.96	0.91
Countermovement Depth (m)	0.01	8.7	17.1	0.92	0.82
Braking Net Impulse (Ns)	3.7	6.6	13.0	0.91	0.82
Avg. Braking Force (N)	1.0	5.5	10.7	0.95	0.91
Peak Braking Force (N)	49.7	7.1	13.8	0.95	0.91
Bodyweight (N)	1.4	0.6	1.3	1.00	1.00
CMJ					
mRSI (ratio)	0.03	10.2	20.0	0.83	0.67
Jump Height (m)	0.00	4.3	8.3	0.92	0.85
Jump Momentum (kg.m/s)	0.28	2.2	4.3	0.97	0.95
Takeoff Velocity (m/s)	0.02	2.1	4.2	0.92	0.85
Time to Take-off (s)	0.02	8.3	16.3	0.78	0.59
Avg. Propulsive Force (N)	10.9	3.7	7.2	0.97	0.94
Peak Propulsive Force (N)	40.7	6.3	12.4	0.95	0.91
Countermovement Depth (m)	0.00	6.8	13.3	0.95	0.91
Braking Net Impulse (Ns)	0.3	5.5	10.8	0.94	0.90
Avg. Braking Force (N)	28.1	8.2	16.0	0.91	0.83
Peak Braking Force (N)	43.9	8.3	16.2	0.94	0.88
Bodyweight (N)	6.4	0.7	1.3	1.00	0.97

Key: CMRJ, countermovement rebound jump; RJ, rebound jump; CMJ, countermovement jump; RSI, reactive strength index; avg., average; mRSI, modified reactive strength index; m, metres; kg, kilograms; s, seconds; N, newtons; CV, coefficient of variation; ICC, intraclass correlation coefficient.

12.4 Poster Presentation at NSCA Conference (New Orleans 2022)

BETWEEN-SESSION RELIABILITY OF THE COUNTERMOVEMENT JUMP AND COUNTERMOVEMENT REBOUND JUMP TESTS IN YOUTH SOCCER PLAYERS

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INTRODUCTION

The countermovement jump (CMJ) is commonly administered in soccer as a test of neuromuscular function during a "slow" (i.e., >250 ms movement time) stretch-shortening cycle (SSC) task. In contrast, the countermovement rebound jump (CMRJ) has been proposed as a test to assess "fast" SSC capacity (i.e., <250 ms contact time), however, the reliability of the CMRJ has yet to be reported.

PURPOSE

The aim of this study was to quantify the between-session reliability of selected force plate metrics obtained during the CMJ (as a reference vertical jump test) and the CMRJ test, in youth soccer players.

METHODS

Male youth soccer players (n = 43, age 17.9 ± 0.9 years, height 181.0 ± 5.8 cm, body mass 72.5 ± 6.8 kg) performed three CMJs and three CMRJs, in a randomized order, on two separate occasions (seven days apart), during the in-season period. Vertical ground reaction forces (vGRFs) were acquired using a dual force plate system (Hawkin Dynamics, Inc.) capturing at 1000 Hz. Athletes stood still for the initial 1 s of both tests to enable the calculation of body weight. Athletes performed all trials with arms akimbo and jumped "as fast and high as possible" (1). The vGRFs were low pass filtered (50 Hz) and analyzed using criterion methods via Hawkin Dynamics, Inc. proprietary software. Numerous jump strategy and outcome variables were reported. Absolute reliability was assessed by coefficient of variation (CV), expressed as a percentage (with ≤5% considered excellent and 5.1-10% considered good). Relative reliability was assessed by a two-way mixed-effects model (average measures) intraclass correlation coefficient (ICC, with 0.75-0.89 considered good and ≥0.9 considered excellent). Upper and lower 95% confidence intervals for the CVs and ICCs, respectively, were calculated to help generalize the reliability scores (2).

RESULTS

Table 1. Absolute and Relative Reliability of the Countermovement Rebound Jump Test.

Metric	CMRJ (CMJ Portion)				CMRJ (RJ Portion)			
	CV%	CV% +95	ICC	ICC -95	CV%	CV% +95	ICC	ICC -95
RSImod/RSI (ratio)	7.4	14.6	0.93	0.88	14.0	27.5	0.87	0.76
Jump Height (m)	5.6	10.9	0.87	0.75	7.2	14.1	0.88	0.77
Jump Momentum (kg.m/s)	2.9	5.7	0.95	0.91	3.5	6.9	0.94	0.89
Takeoff Velocity (m/s)	4.3	8.3	0.75	0.54	4.8	9.4	0.81	0.66
TTT/GCT (s)	8.1	15.8	0.83	0.69	13.0	25.5	0.87	0.71
Avg. Propulsive Force (N)	3.8	7.5	0.96	0.92	6.8	13.4	0.90	0.79
Peak Propulsive Force (N)	6.2	12.1	0.96	0.91	9.3	18.2	0.93	0.87
CM/Braking Depth (m)	8.7	17.1	0.92	0.82	20.2	39.6	0.88	0.74
Braking Net Impulse (Ns)	6.6	13.0	0.91	0.82	3.1	6.1	0.95	0.90
Avg. Braking Force (N)	5.5	10.7	0.95	0.91	7.9	15.5	0.91	0.83
Peak Braking Force (N)	7.1	13.8	0.95	0.91	9.1	17.7	0.93	0.86

All variables showed good-excellent relative reliability (ICC >0.75). All CMJ and CMJ portion of CMRJ variables showed good-excellent absolute reliability (<10%). Absolute reliability was unacceptable for reactive strength index (RSI), contact time, and braking depth for the rebound jump (RJ) portion of CMRJ (Table 1).

CONCLUSIONS

Most CMJ and CMRJ (Table 1) variables are reliable for male youth soccer players. The greater between-session variability in RJ braking depth (20%), contact time (13%) and RSI (14%) reveals some inconsistencies in RJ strategy. The variability in RJ strategy was not considered to be due to changes in the preceding jump height from the CMJ phase of the CMRJ, as this showed low variability (~6%).

PRACTICAL APPLICATIONS

The CMRJ shows promise as a test of fast SSC ability in youth soccer players but more familiarity with the test is likely needed to further reduce between-session variability and thus increase the sensitivity of the test.

REFERENCES

1. McMahon, J, Lake, J, Stratford, C, and Comfort, P. A proposed method for evaluating drop jump performance with one force platform. *Bicmech* 1(2): 178-189, 2021.
2. Cormack, S, Newton, R, McGuigan, M, and Doyle, T. Reliability of Measures Obtained During Single and Repeated Countermovement Jumps. *Int J Sports Physiol Perform* 3(2): 131-144, 2008.

12.5 Additional Chapter 9 Results Tables

Table 1. Individual Percentage Change in Metric Values Following a Competitive Soccer Match in Youth Soccer Players.

Name	Body Weight (%)			Net Braking Impulse (%)			Countermovement Depth (%)			Propulsive Phase Time (%)			Peak Propulsive Force (%)		
	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2
Player 1	-1.20	2.71	1.47	-8.27	9.80	0.73	-6.23	0.01	-6.22	-0.72	3.07	2.33	-0.72	3.07	2.33
Player 2	-2.18	2.55	0.32	4.74	-5.42	-0.94	-0.08	-4.46	-4.54	1.90	-0.43	1.47	1.90	-0.43	1.47
Player 3	-1.22	3.15	1.90	4.14	19.27	24.22	5.49	3.84	9.54	-6.93	2.37	-4.72	-6.93	2.37	-4.72
Player 4	-2.00	1.63	-0.41	-3.48	-1.63	-5.05	-3.37	9.04	5.37	-3.63	-4.92	-8.37	-3.63	-4.92	-8.37
Player 5	-1.82	3.45	1.56	7.58	18.24	27.20	5.99	9.31	15.86	-2.42	7.45	4.85	-2.42	7.45	4.85
Player 6	-2.40	2.26	-0.20	-8.14	28.29	17.85	-3.20	19.50	15.68	-3.25	3.69	0.32	-3.25	3.69	0.32
Player 7	-0.76	3.37	2.58	3.39	-3.15	0.13	-3.82	3.48	-0.47	1.60	-5.93	-4.43	1.60	-5.93	-4.43
Player 8	-1.90	2.19	0.24	-1.11	17.31	16.00	-7.53	13.67	5.11	1.00	6.08	7.15	1.00	6.08	7.15
Player 9	-0.82	0.74	-0.09	-2.51	0.43	-2.09	4.60	-8.55	-4.35	-9.48	9.59	-0.80	-9.48	9.59	-0.80
Player 10	-0.67	-0.43	-1.09	-3.92	-0.47	-4.36	-3.18	3.35	0.07	-4.62	2.84	-1.91	-4.62	2.84	-1.91
Player 11	-0.29	3.04	2.75	-13.22	-3.26	-16.05	-15.17	-5.24	-19.62	1.10	-1.06	0.04	1.10	-1.06	0.04
Player 12	-2.13	0.82	-1.33	-0.98	3.01	2.00	-0.35	5.93	5.56	-7.00	3.96	-3.32	-7.00	3.96	-3.32
Player 13	-3.48	2.55	-1.03	-16.57	18.67	-1.00	-13.51	12.27	-2.89	7.50	-3.16	4.10	7.50	-3.16	4.10
Player 14	-2.11	1.74	-0.41	-21.49	5.81	-16.92	-4.85	4.73	-0.35	-0.13	-3.43	-3.56	-0.13	-3.43	-3.56
Player 15	-2.84	2.28	-0.62	-9.59	6.64	-3.59	1.75	5.95	7.81	-8.64	-3.79	-12.10	-8.64	-3.79	-12.10
Player 16	-1.81	1.89	0.05	-0.84	4.92	4.04	-1.17	0.00	-1.17	5.31	-3.84	1.27	5.31	-3.84	1.27
Player 17	-0.74	2.28	1.52	-4.90	10.33	4.92	-1.70	2.29	0.55	-6.63	3.84	-3.05	-6.63	3.84	-3.05
Player 18	-1.64	2.09	0.42	-8.43	9.45	0.22	7.90	10.32	19.03	-15.76	3.61	-12.72	-15.76	3.61	-12.72
Player 19	-0.65	1.26	0.61	-18.54	18.41	-3.54	-1.75	12.48	10.52	3.75	-5.51	-1.97	3.75	-5.51	-1.97
Player 20	-1.21	2.54	1.30	-4.27	0.29	-3.99	-11.00	-1.53	-12.36	2.30	-0.70	1.58	2.30	-0.70	1.58
Player 21	-0.83	0.75	-0.08	-14.86	6.40	-9.41	-13.54	-5.77	-18.53	11.17	-4.79	5.84	11.17	-4.79	5.84
Player 22	-1.31	1.03	-0.29	-15.28	8.52	-8.06	9.23	11.32	21.60	-6.13	-6.83	-12.55	-6.13	-6.83	-12.55
Player 23	-1.36	2.58	1.19	-14.82	0.83	-14.11	5.56	0.27	5.84	-8.41	2.99	-5.67	-8.41	2.99	-5.67
Player 24	-2.00	2.18	0.13	4.94	-2.37	2.45	-2.77	6.56	3.61	1.46	-5.60	-4.22	1.46	-5.60	-4.22
Player 25	-1.80	2.72	0.87	-10.66	11.80	-0.11	-12.85	12.24	-2.18	-1.76	-1.41	-3.15	-1.76	-1.41	-3.15
Player 26	-1.80	4.28	2.40	-17.70	20.60	-0.75	1.93	-2.96	-1.08	-4.48	2.60	-1.99	-4.48	2.60	-1.99
Player 27	-1.71	2.28	0.53	-30.25	42.22	-0.80	-5.21	11.05	5.26	-14.42	18.25	1.20	-14.42	18.25	1.20

Table 1. (Continued).

Name	Mean Propulsive Force (%)			Peak Velocity (%)			Mean Propulsive Velocity (%)			Peak Propulsive Power (%)			Mean Propulsive Power (%)		
	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2
Player 1	-1.91	1.58	-0.37	-3.30	-2.13	-5.36	-2.67	-2.05	-4.67	-2.73	-0.89	-3.60	-5.07	-0.36	-5.41
Player 2	2.16	-4.16	-2.09	3.83	-5.60	-1.98	4.01	-7.50	-3.78	4.12	-5.52	-1.63	6.14	-10.51	-5.02
Player 3	-7.51	3.35	-4.42	-2.69	-0.62	-3.29	-4.84	0.74	-4.13	-5.83	0.84	-5.04	-10.85	3.53	-7.71
Player 4	2.41	-7.30	-5.07	1.91	-3.23	-1.38	1.93	-3.00	-1.13	4.15	-8.65	-4.86	3.84	-9.78	-6.31
Player 5	-3.52	-1.97	-5.42	2.20	-2.64	-0.50	-2.04	4.14	2.02	3.38	-7.81	-4.69	-3.38	-1.31	-4.64
Player 6	-2.66	-1.82	-4.43	0.83	-0.06	0.76	-4.54	5.95	1.14	1.38	-5.00	-3.69	-4.51	1.70	-2.89
Player 7	4.14	-5.40	-1.48	3.58	-5.03	-1.63	2.79	-6.08	-3.46	11.15	-9.60	0.48	7.02	-10.20	-3.89
Player 8	4.51	-2.09	2.33	7.16	-4.91	1.90	4.91	-2.70	2.08	15.27	-10.45	3.22	10.10	-5.21	4.36
Player 9	-8.36	8.50	-0.57	-2.10	2.40	0.25	-6.52	5.17	-1.68	-3.62	6.52	2.67	-12.25	12.27	-1.48
Player 10	2.80	-3.92	-1.22	5.09	-4.63	0.23	2.37	-1.66	0.67	8.41	-10.71	-3.20	6.50	-6.55	-0.48
Player 11	1.12	-0.85	0.26	-3.62	-6.57	-9.94	-6.76	-5.01	-11.44	1.49	-8.11	-6.73	-4.50	-6.37	-10.59
Player 12	-1.08	-1.58	-2.64	1.81	-0.23	1.57	-1.40	0.34	-1.06	3.36	-0.21	3.15	-0.74	-1.56	-2.28
Player 13	3.74	-1.37	2.32	2.35	-0.86	1.47	0.41	2.17	2.59	8.12	-4.48	3.28	4.89	-0.74	4.11
Player 14	-0.53	-2.63	-3.14	0.10	-2.54	-2.44	-3.82	-0.78	-4.57	5.68	-7.84	-2.61	-2.46	-4.31	-6.67
Player 15	-8.49	-0.18	-8.65	-2.42	-0.60	-3.01	-8.87	2.53	-6.57	-3.81	-4.63	-8.27	-13.37	1.11	-12.41
Player 16	2.97	-1.44	1.49	4.22	-3.97	0.08	2.59	-1.14	1.43	9.76	-8.26	0.69	6.27	-3.86	2.17
Player 17	-4.98	2.74	-2.38	-3.39	-0.62	-3.99	-7.29	3.56	-3.98	-3.76	-2.95	-6.60	-10.06	4.39	-6.11
Player 18	-8.33	-2.12	-10.27	-1.04	-0.56	-1.59	-5.52	1.20	-4.39	-4.38	-3.20	-7.44	-10.98	-1.56	-12.37
Player 19	-0.37	-1.55	-1.91	0.16	1.22	1.38	-2.51	3.27	0.67	5.28	-4.68	0.35	-1.77	1.06	-0.73
Player 20	-1.36	0.16	-1.21	-2.85	-5.63	-8.32	-1.74	-4.94	-6.60	-1.05	-6.03	-7.02	-4.16	-5.07	-9.02
Player 21	1.22	2.42	3.67	-2.53	-3.32	-5.77	-4.28	-0.11	-4.39	2.88	-6.51	-3.82	-2.74	1.24	-1.53
Player 22	-10.96	-2.37	-13.07	-1.94	0.60	-1.35	-9.16	1.75	-7.57	-4.99	-4.41	-9.17	-15.64	-0.95	-16.44
Player 23	-5.91	2.91	-3.17	0.67	-2.42	-1.77	-4.00	-0.97	-4.93	-1.20	-3.29	-4.44	-7.38	1.30	-6.17
Player 24	4.93	-9.52	-5.07	5.62	-8.52	-3.38	5.13	-6.93	-2.15	9.47	-17.88	-10.10	10.27	-15.68	-7.02
Player 25	2.39	-4.31	-2.01	-0.04	-4.23	-4.27	-0.99	-3.39	-4.34	5.10	-11.93	-7.43	1.36	-7.21	-5.95
Player 26	-11.49	12.06	-0.81	-3.66	0.36	-3.31	-14.36	11.71	-4.34	-3.49	-0.22	-3.70	-19.34	18.75	-4.22
Player 27	-13.39	12.59	-2.49	-10.02	7.69	-3.10	-17.68	19.73	-1.43	-13.12	5.50	-8.35	-24.80	26.73	-4.70

Table 1. (Continued).

Name	Net Impulse Ratio (%)			Takeoff Velocity (%)			Jump Momentum (%)			Flight Time (%)			Jump Height (%)		
	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2	Pre- vs Post	Post- vs MD+2	Pre- vs MD+2
Player 1	3.24	-8.49	-5.52	-3.89	-2.14	-5.94	-5.05	0.51	-4.56	-4.24	-0.78	-4.99	-7.62	-4.21	-11.51
Player 2	-2.70	1.59	-1.14	3.96	-6.02	-2.30	1.69	-3.62	-1.99	4.63	-6.10	-1.76	8.08	-11.68	-4.55
Player 3	-8.71	-13.57	-21.10	-3.52	-0.29	-3.80	-4.70	2.85	-1.98	-2.46	-0.60	-3.04	-6.91	-0.61	-7.48
Player 4	2.45	-0.63	1.80	1.74	-3.99	-2.32	-0.30	-2.43	-2.72	4.18	-5.67	-1.72	3.53	-7.84	-4.59
Player 5	-5.84	-16.46	-21.34	2.37	-4.08	-1.81	0.51	-0.78	-0.27	2.29	-2.91	-0.68	4.81	-8.02	-3.60
Player 6	7.42	-20.51	-14.61	1.54	-0.42	1.11	-0.90	1.82	0.91	1.93	-1.63	0.27	3.12	-0.85	2.24
Player 7	-0.95	1.23	0.27	3.42	-5.23	-1.99	2.64	-2.04	0.54	3.90	-5.74	-2.07	6.95	-10.19	-3.94
Player 8	7.44	-17.77	-11.66	7.69	-4.91	2.41	5.64	-2.83	2.66	6.23	-2.69	3.37	16.05	-9.62	4.88
Player 9	-2.03	3.79	1.69	-3.26	3.27	-0.10	-4.06	4.03	-0.19	-0.62	4.47	3.82	-6.42	6.63	-0.21
Player 10	8.97	-4.73	3.82	5.77	-4.86	0.63	5.06	-5.27	-0.47	4.31	-4.31	-0.18	11.89	-9.47	1.30
Player 11	11.07	-1.22	9.71	-3.76	-6.99	-10.49	-4.04	-4.16	-8.03	-6.74	-6.04	-12.38	-7.37	-13.51	-19.88
Player 12	1.39	-2.71	-1.36	2.61	-0.59	2.00	0.42	0.22	0.65	1.64	1.89	3.56	5.33	-1.21	4.06
Player 13	19.02	-14.39	1.90	2.94	-1.16	1.74	-0.64	1.35	0.70	1.87	-0.43	1.43	5.97	-2.33	3.50
Player 14	25.38	-6.79	16.86	-0.03	-2.89	-2.92	-2.13	-1.20	-3.31	-1.07	-2.99	-4.03	0.00	-5.76	-5.76
Player 15	4.97	-4.54	0.21	-2.60	-0.32	-2.91	-5.36	1.96	-3.51	-5.22	0.31	-4.93	-5.04	-0.73	-5.73
Player 16	3.62	-7.13	-3.77	4.47	-4.31	-0.04	2.58	-2.50	0.01	3.92	-5.40	-1.69	9.13	-8.38	-0.01
Player 17	0.10	-7.27	-7.17	-3.95	-0.30	-4.24	-4.67	1.98	-2.79	-4.16	0.29	-3.88	-7.72	-0.65	-8.32
Player 18	6.80	-8.72	-2.52	-1.60	-1.11	-2.69	-3.21	0.95	-2.28	-0.74	-1.36	-2.09	-2.93	-2.46	-5.32
Player 19	20.92	-13.29	4.85	-0.27	1.67	1.39	-0.92	2.95	2.01	-1.19	2.95	1.73	-0.54	3.36	2.80
Player 20	-0.62	-3.86	-4.45	-3.84	-5.97	-9.58	-5.00	-3.58	-8.40	-5.35	-4.39	-9.51	-7.47	-11.62	-18.22
Player 21	13.10	-6.54	5.71	-2.83	-2.33	-5.10	-3.64	-1.60	-5.18	-3.72	-1.96	-5.61	-5.59	-4.58	-9.91
Player 22	13.62	-6.06	6.74	-2.56	0.85	-1.73	-3.84	1.89	-2.01	-2.91	-0.85	-3.73	-5.06	1.70	-3.44
Player 23	16.18	1.87	18.35	0.20	-1.92	-1.73	-1.16	0.61	-0.56	1.91	-0.13	1.78	0.41	-3.80	-3.41
Player 24	-0.41	-5.55	-5.93	6.82	-9.83	-3.69	4.68	-7.87	-3.56	8.17	-11.19	-3.94	14.14	-18.70	-7.21
Player 25	9.76	-11.84	-3.24	-0.37	-3.78	-4.14	-2.17	-1.16	-3.30	-0.66	-3.63	-4.27	-0.73	-7.44	-8.12
Player 26	16.57	-14.30	-0.11	-4.12	1.15	-3.02	-5.85	5.47	-0.70	-7.14	4.40	-3.06	-8.05	2.31	-5.93
Player 27	25.69	-21.84	-1.76	-11.03	8.71	-3.28	-12.55	11.19	-2.77	-11.87	9.97	-3.08	-20.84	18.19	-6.44

12.6 Other Notable Contributions to Research

Presented at:

ISBS (Liverpool) 2022. Badby, A.J., Mundy, P., Comfort, P., Lake, J. and McMahon, J.J., 2022. Agreement among countermovement jump force-time variables obtained from a wireless dual force plate system and an industry gold standard system. ISBS Proceedings Archive, 40(1), p.58 [163]; *(see Appendices for Abstract and Poster).*

NSCA National Conference (New Orleans) 2022. Badby, A.J., et al., Between-Session Reliability of the Countermovement Jump and Countermovement Rebound Jump Tests in Youth Soccer Players, NSCA 2022 National Conference Abstracts. The Journal of Strength & Conditioning Research, 2022. 37(3): p. E36-E37 [58]; *(see Appendices for Abstract and Poster).*

Published in:

MDPI Sensors. Badby, A.J., Mundy, P.D., Comfort, P., Lake, J.P. and McMahon, J.J., 2023. The validity of Hawkin Dynamics wireless dual force plates for measuring countermovement jump and drop jump variables. Sensors, 23(10), p.4820 [21].

Co-authorship in:

McMahon, J.J., Jones, P.A., Badby, A.J., Ripley, N.J. and Comfort, P., 2021. The eccentric utilization ratio is influenced by between-jump differences in propulsion displacement. The Journal of Strength & Conditioning Research, 35, pp.e107-e108 [61].

McMahon, J.J., Comfort, P., Jones, P.A., Cuthbert, M. and Badby, A.J., 2022. Early pre-season changes in the countermovement jump outcome and strategy variables of English Super League rugby players. ISBS Proceedings Archive, 40(1), p.443 [62].

McMahon, J.J., Ripley, N.J., Comfort, P., Robles-Palazón, F.J., Fahey, J.T., Badby, A.J. and Bramah, C., 2023. The Kneeling Isometric Plantar Flexor Test: Preliminary Reliability and Feasibility in Professional Youth Football. Journal of Functional Morphology and Kinesiology, 8(4), p.164 [63].

Informed data collection, analysis, and statistical methodologies of:

Dos' Santos, T., Evans, D.T. and Read, D.B., 2024. Validity of the Hawkin Dynamics wireless dual force platform system against a piezoelectric laboratory grade system for vertical countermovement jump variables. The Journal of Strength & Conditioning Research, 38(6), pp.1144-1148.

13 ETHICS APPROVAL

ethics
Thu 08/07/2021 15:20
To: Andrew Badby
Cc: John Mcmahon

Dear Andrew,

RE: ETHICS APPLICATION Ref. 2216 : *DEVELOPING A FORCE PLATE TESTING BATTERY FOR MONITORING LOWER BODY NEUROMUSCULAR FUNCTION - RELIABILITY AND BENCHMARKING.*

Based on the information that you have provided, I am pleased to inform you that application Ref. 2216 has been approved by the Chair.

The Chair has stated that this approval is provisional upon you uploading the material provided to the chair once you again have access to the online system, in order to remain compliant with ethical approval. Also, please send the video viewed by the Chair to ethics@salford so that we can a copy for our records.

If there are any changes to the project and/or its methodology, then please inform the Panel as soon as possible by contacting Ethics@salford.ac.uk.

Kind Regards,

The Ethics Team

Figure 13.1. Ethical Approval for Reliability and Benchmarking Chapters (08/07/2021).

ethics
Mon 27/09/2021 16:25
To: Andrew Badby
Cc: John Mcmahon

The Ethics Panel has reviewed your application: DEVELOPING A FORCE PLATE TESTING BATTERY FOR MONITORING LOWER BODY NEUROMUSCULAR FUNCTION - CONCURRENT VALIDITY.
Application ID: 2768

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.

Figure 13.2. Ethical Approval for Validity Chapter (27/09/2021).

Subject: Ethics Application: Panel Decision
Date: Friday, 29 September 2023 at 10:50:07 British Summer Time
From: ethics
To: Andrew Badby
CC: John Mcmahon
Priority: Low

The Ethics Panel has reviewed your application: MONITORING ACUTE CHANGES IN COUNTERMOVEMENT JUMP NEUROMUSCULAR FUNCTION IN SOCCER ATHLETES
Application ID: 13157

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

Figure 13.3. Ethical Approval for Monitoring Chapter (29/09/2023).

14 GANTT CHART OF PROGRESS AND PLANNING PRESENTED AT INTERNAL EVALUATION

Table 1. Plan of Year 1 (2021/2022).

Year	Year 1											
Month	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**January**	**February**	**March**	**April**
Scoping Review							Planning & Reading					
Study 1 Data Collection						Data Collected						
Study 1 Write-Up									Write-Up Abstract Format (ISBS 2022)			
Study 2 Data Collection		Start of Data Collection (Pre-Season)										
Study 2 Write-Up						Write-Up Abstract Format (NSCA 2022)						
Study 3 Data Collection		Start of Data Collection (Pre-Season)										
Study 3 Write-Up												
Study 4 Data Collection												
Study 4 Write-Up												
Additional	General Preparation, Registration, Ethics Applications, etc.								Introduction and Literature Review Write-Up			

Table 2. Plan of Year 2 (2022/2023).

Year	Year 2											
Month	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**January**	**February**	**March**	**April**
Scoping Review	Collection, Interpretation, and Writing of Results						Remaining Write-Up Thesis Format				**Internal Evaluation** (Month 21-23)	Completion
Study 1 Data Collection												
Study 1 Write-Up			**<u>ISBS 2022</u>**				Write-Up Thesis Format					Feedback Edits
Study 2 Data Collection		Final Data Collection (Pre-Season)				Data Collection (In-Season)						
Study 2 Write-Up			**<u>NSCA 2022</u>**				Write-Up Thesis Format					Feedback Edits
Study 3 Data Collection		Additional Data Collection (Pre-Season)										
Study 3 Write-Up		Collation of Current Information				Start of Plans on Write-Up						Feedback Plan
Study 4 Data Collection												
Study 4 Write-Up						Start of Plans on Design						Ethics
Additional	**<u>ISCC 2022</u>**	**<u>HD Work</u>**		General Methods Collation and Write-Up								

Table 3. Plan of Year 3 (2023-2024).

Year	Year 3											
Month	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**January**	**February**	**March**	**April**
Scoping Review	Feedback Edits										**Final Edits**	**Start of Potential Thesis Submission**
Study 1 Data Collection												
Study 1 Write-Up	Feedback Edits											
Study 2 Data Collection												
Study 2 Write-Up	Feedback Edits											
Study 3 Data Collection		Final Data Collection (Pre-Season)										
Study 3 Write-Up	Feedback Plan	Write Introduction and Methods Chapters			Write Results and Discussion Chapters			Gain and Address Feedback				
Study 4 Data Collection		Data Collection (Pre-Season)										
Study 4 Write-Up	Ethics	Write Introduction and Methods Chapters			Write Results and Discussion Chapters			Gain and Address Feedback				
Additional		Focus on Publications (Studies 1 and 2)										

Table 4. Plan of Year 4 (2024/2025).

Year	Year 4											
Month	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**January**	**February**	**March**	**April**
Scoping Review						**3.5 Years Approx. Viva Voce**						
Study 1 Data Collection												
Study 1 Write-Up												
Study 2 Data Collection												
Study 2 Write-Up												
Study 3 Data Collection												
Study 3 Write-Up												
Study 4 Data Collection												
Study 4 Write-Up												
Additional	Viva Prep											