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Quantifying neuromuscular performance of elite rugby union players: Measurement characteristics and moderating factors

by

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Certificate of Authorship and Originality of Thesis

I, David Howarth, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Sport, Exercise and Rehabilitation, Faculty of Health, at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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"If I have seen further than others, it is by standing on the shoulders of giants."

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Publications

Published Articles

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Howarth, D. J., McLean, B. D., Cohen, D. D., & Coutts, A. J. Removing the noise: An agnostic approach to data reduction for monitoring changes in countermovement jump kinetic variables.

Howarth, D. J., McLean, B. D., Cohen, D. D., & Coutts, A. J. Neuromuscular responses to training load in professional rugby union players

Preface

This thesis for the degree of Doctor of Philosophy is in the format of published or submitted manuscripts and abides by the 'Procedures for Presentation and Submission of Theses for Higher Degrees – University of Technology Sydney; Policies and Directions of the University'.

Based on the research design and data collected by the candidate, two manuscripts have been accepted for publication and three are ready to be submitted, in peer-reviewed journals. These papers are initially brought together by an *Introduction*, which provides background information, defines the research problem and the aim of each study. A *Literature Review* provides an overview of previous knowledge that defines neuromuscular status, examines the countermovement jump as a means of assessing change in it, and why it is an important factor in the management of professional rugby union players. A logical sequence following the development of research ideas in this thesis is presented in manuscript form (*Chapter 3 to Chapter 7*). Each manuscript outlines and discusses the individual methodology and the findings of each study separately. The *Discussion* chapter provides an interpretation of the collective findings and practical applications from the series of investigations conducted. The APA reference style has been used throughout the document and the reference list is at the end of the thesis.

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List of Abbreviations

$Best_{JH}$	Single output from the highest jump
$Best_{FTCT}$	The trial with the highest flight time: contraction time ratio
CI	Confidence interval
cm	Centimetre
CMJ	Countermovement jump
CNS	Central nervous system
CV%	Coefficient of variation
d	Cohens d effect size
df	Degrees of freedom
Decel	Deceleration
Ecc	Eccentric
EDRFD	Eccentric deceleration rate of force development
ES	Effect size
EMG	Electromyographs
F	Force
FTCT	Flight time: contraction time ratio
GPS	Global positioning system
HSR	High-speed running
ICC	Intraclass correlation coefficient
J	Joule
kg	Kilogram
$Mean_3$	Mean output across 3 jump trials
ms	Millisecond

MSA	Keyser-Meyer-Olkin Measure of Sampling Adequacy statistic
N	Newton
PCA	Principal component analysis
PNS	Peripheral nervous system
RFD	Rate of force development
RPD	Rate of power development
RT	Resistance training volume load
s	Second
SNR	Signal-to-noise ratio
sRPE	Session rate of perceived exertion
SSC	Stretch-shortening cycle
TD	Total distance
VHSR	Very high-speed running distance (distance covered >75% of maximum velocity)
VO_2 max	Maximum oxygen consumption
W	Watt

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Abstract

This thesis investigates the neuromuscular status of elite rugby union players, focusing on the practical application of countermovement jump (CMJ) testing to monitor changes in neuromuscular function throughout a competitive season. This work grounded in the understanding that neuromuscular status —encompassing muscle strength, power output, and coordination—plays a critical role in an athlete's performance and recovery. Consequently, this thesis explores the utility of the CMJ—a practical, non-invasive measure that incorporates the stretch-shortening cycle (SSC) and provides an assessment of explosive power and neuromuscular efficiency—in the monitoring of professional rugby players.

The aims of the thesis are examined through four studies, each focusing on different aspects of CMJ analysis relevant to elite sports performance. Study 1 investigates the inter-day ecological reliability of a range of CMJ kinetic variables in professional rugby union players. Using ecologically valid protocols that examine test/re-test reliability at different day and time intervals, this work explores the expected amounts of methodological and biological variation for each CMJ variable used to examine neuromuscular status through relative and absolute reliability analysis. Additionally, the difference between data treatment methods (i.e., average of 3 jumps vs a "best" jump) is investigated, mirroring protocols that have been used in research and practice, with the results showing that reliability can be established using any 2-day combination within the first week of pre-season training. Study 2 expands on this work by examining the sensitivity of CMJ variables by comparing the day-to-day variation – found in reliability analysis – to the week-to-week variation created by training and competition stimuli over a playing season. By again evaluating different data treatment methods, this study provides insights into the practical applications of longitudinal tracking of CMJ variables, specifically the use of single vs multiple jump results, where using the average of 3 jumps or

the results from the jump with the best flight-time/contraction-time ratio provide similar levels of sensitivity in CMJ variables.

Study 3 utilises principal component analysis (PCA) to explore CMJ variable covariance, in order to agnostically reduce data complexity without losing critical information by arbitrary exclusion of variables before analysis. This study emphasises the need for a comprehensive examination of variable redundancy by finding that metrics from each phase of the jump can be reduced to 2-5 groups of highly correlated variables, aiding practitioners in selecting the most informative CMJ metrics for monitoring neuromuscular status. Study 4 focuses on the neuromuscular response to recent cumulative training loads, employing an integrated approach that includes running volumes, resistance training volume, and session rate of perceived exertion load, to elucidate the effects of different types of training stimuli on neuromuscular function. The findings show the differential effects of load on neuromuscular status depending on when it is measured in relation to the game, highlighting the nuanced temporal effects of fatigue alongside the varied neuromuscular response to different types of load (i.e., running vs perceived difficulty vs resistance training).

Chapter 6 is a technical report that outlines a framework for selecting a manageable number of CMJ variables for longitudinal monitoring. This framework is built on the essential measurement characteristics of reliability, sensitivity, and covariance, and proposes a systematic approach to CMJ variable selection that enhances the precision of athlete monitoring systems. By integrating these methods with practitioner expertise, the report offers a model for practical implementation in a data-informed sports performance environment.

This thesis demonstrates the use of agnostic statistical techniques that progressively build practitioner understanding of CMJ variables as reliable and sensitive markers of neuromuscular status. The use of PCA for data reduction presents a novel approach to simplifying the monitoring process, while the comprehensive examination of cumulative training loads offers valuable insights into the temporal dynamics of fatigue and recovery. This thesis fills a critical gap in current sports science knowledge by providing a practical, evidence-based framework for monitoring neuromuscular status in professional rugby union players. The results of these studies differ from previous investigations, showing greater levels of both reliability and sensitivity in variables previously investigated, and by exploring a greater total number of variables. These results can be attributed to the methodological and statistical rigor employed, which are unique to prior research conducted in applied settings. Collectively, these results culminate in a demonstrable link between the selected CMJ variables and changes in training load, supporting the use of CMJ as a robust tool for detecting meaningful changes in neuromuscular status.

Chapter 1

Introduction

1.1. Background

The optimisation of training programs to achieve peak performance in elite athletes is a well-established goal in sports science (Kiely, 2012). This endeavour is particularly complex in field sports such as rugby union, where the physical demands require a fine balance of strength, endurance, and skill adaptations (Jones, Smith, et al., 2017). Periodised training plans, which systematically structure training intensity, volume, and modality across different phases, have traditionally been used in efforts to optimally prepare athletes (Bompa & Haff, 2009). These plans are based on the principle of progressive overload, which involves gradually increasing stress to stimulate adaptation, thereby enhancing athletic performance while minimising the risk of overtraining and injury (Bompa & Haff, 2009; Issurin, 2010).

In rugby union, the nature of the game demands concurrent training strategies due to the overlapping requirements of strength, endurance, and skill (Jones et al., 2016). A major challenge in applying this approach is that simultaneous stimuli compound to create fatigue and interfere with the separate goals of that training (Hickson, 1980). Strategic sequencing and balancing of training modalities can mitigate these interference effects, but such a balance emphasises the need for tailored plans that align with the individual responses of the athlete, which are heavily influenced by the competitive calendar (Jones et al., 2016). When managed well, concurrent training allows athletes to develop multiple physical qualities simultaneously, which is essential for meeting the diverse demands of rugby union (Kiely, 2012), making it extremely beneficial for athletes in sports that require a mix of physical capabilities.

1.1.1. Neuromuscular status and its importance in team sport performance

"Neuromuscular status" is a term commonly used in athlete preparation literature and refers to the current condition of an athlete's neuromuscular system, which includes muscle strength, power output, coordination, and fatigue resistance (Enoka & Duchateau, 2016). The key functional unit of the neuromuscular system is the motor unit, comprised of the motor nerve and muscle fibres it innervates (Shepherd, 1994). Neuromuscular status is dynamic, and often described as fluctuating along a fitness-fatigue continuum in response to training loads and recovery processes (Cormack, Newton, McGuigan, & Cormie, 2008; Coutts et al., 2018). Understanding these fluctuations within individual athletes can assist practitioners in optimising training programs and reducing the risk of injuries.

One aspect of neuromuscular function that is particularly important in explosive tasks in team sports is the stretch shortening cycle (SSC). Actions involving the SSC (e.g. jumping and sprinting) are typified by the presence of a rapid eccentric contraction (muscle lengthens under tension) immediately followed by a concentric contraction (muscle shortens) (Komi & Bosco, 1978). The efficiency and output of the SSC have been reported to be explained by two overarching models: the neuromuscular model and the mechanical model (Komi, 1984). The neuromuscular model is based on the stretch reflex governed by the muscle spindle, which provides information to the CNS on the velocity of change in muscle length (Komi, 1984). When a muscle lengthens rapidly, the CNS responds by sending an opposing signal via alpha motor neurons for it to contract, creating a potentiation effect for greater contraction force during the subsequent concentric contraction (Komi, 1984). The mechanical model is based on the elastic capacity of the muscle-tendon complex, which returns rapidly to shape after being stretched by an external force (Komi, 1984). The combination of these models contributes to the enhanced force production observed in SSC movements compared to concentric only actions (Komi & Bosco, 1978). Given that these elastic properties take significant training and time to change (Hennessy & Kilty, 2001; Komi, 1984), acute (i.e., within 124 hours of fatiguing activity) changes in the force produced during SSC activities are more likely to be due to neural factors related to fatigue, making these movements useful in the evaluation of neuromuscular status (Nicol et al., 2006).

1.1.2. Tools for monitoring neuromuscular status

Given the importance of neuromuscular function in athletic performance, numerous tools have been developed to assess neuromuscular status. For example, electromyography (EMG) has been extensively used to measure the electrical activity arising from motor unit recruitment as a way of providing insights into neuromuscular function in both fatigued states and competitive periods (Boccia et al., 2015; Miramonti et al., 2016). However, the practical application of EMG testing in elite sports settings can be challenging due to the time it takes to conduct testing and the complexity of the test procedures. To address such challenges, the countermovement jump (CMJ) has emerged as a practical, and widely used, tool for monitoring neuromuscular status in team sports. The CMJ inherently incorporates the SSC, allowing the evaluation of 3 phases of movement (eccentric, concentric, and landing), thereby providing a comprehensive measure of an athlete's explosive power and neuromuscular efficiency (Nicol et al., 2006; Sole et al., 2018).

1.1.3. The relevance of CMJ monitoring in team sports

The CMJ as an assessment tool is well-examined within the literature, with several investigations demonstrating strong correlations with other dynamic tasks, such as sprint performance (Cronin & Hansen, 2005; Hennessy & Kilty, 2001; Hermassi et al., 2014). These findings highlight its utility in evaluating an athlete's ability to generate lower extremity power and impulse (Markström & Olsson, 2013). The CMJ is also a practical test to run, as despite the maximal nature of the test, there is low residual fatigue from completing the test. This means that the stretch-shortening cycle can be assessed regularly, offering some insight to the fluctuations in status of the neuromuscular system.

While CMJ performance can be assessed in many ways using force plates, ground reaction force measures can provide detailed kinetic analysis related to the athlete's neuromuscular performance. This can be achieved using force platforms, which have become more accessible in recent years, making this type of detailed analysis of the athlete's neuromuscular performance more accessible to practitioners and researchers. Foundational research in this area by Cormie et al. (2009) identified significant differences in CMJ metrics between athletes with varying jump capabilities, highlighting the tool's sensitivity to neuromuscular adaptations. The CMJ performed don force platforms is also easy to implement, requires little familiarisation, and is a quick test , making it a practical and popular tool for monitoring neuromuscular status in elite sports settings. However, interpreting the information gathered from such assessments can be challenging due to the specialised nature of biomechanical measurement and the sheer volume of metrics calculated. Understanding the measurement characteristics (e.g., reliability and sensitivity), identifying the key variables are important to track and compare, and most importantly, how to utilise the information (i.e., action items once data is assessed) are crucial for effective and efficient use in these settings.

1.2. Statement of the problem

Despite the advancements in training methodologies and monitoring tools, quantifying the neuromuscular status of elite athletes remains a significant challenge. The neuromuscular system, encompassing muscle strength, power output, coordination, and fatigue resistance, is dynamic and responsive to training loads and recovery processes. Understanding the acute and chronic responses of this system to different training stimuli is crucial for optimising performance and preventing injury.

While various methods exist for assessing neuromuscular status, their complexity and lack of practicality in executing the tests hinders effectiveness in elite sports settings. The CMJ, due to its integration of the SSC and its comprehensive measurement capabilities, offers a practical solution. However, the specific application of CMJ metrics in team sports, particularly at the elite level, requires further exploration. Specifically for rugby union, the existing literature primarily focuses on sub-elite athletes or limited timeframes, leaving a gap in understanding how CMJ metrics correlate with the unique demands of training and game play over an entire season.

1.3. Research objectives

This thesis aims to develop methods for better understanding and utilising the most meaningful information obtained from CMJ testing in the context of a given sport and situations in which the testing is conducted. To achieve this, the series of studies presented here explore the measurement characteristics of CMJ, employ agnostic statistical techniques to inform variable reduction, and produce expert-informed parsimonious systems that meet the needs of practitioners and athletes in various environments.

This work is explored in the context of rugby union players throughout a professional season, but the goal is to develop techniques that may be applied in various scenarios (i.e., not just in rugby union and not just in the context of a long season) to understand this information specific to each given context. To accomplish this, a methods section outlines how statistical methods can be integrated and combined with practitioner expertise, including knowledge of desired training outcomes, to select the most meaningful variables from the CMJ to inform training status. Then, a series of three studies is presented to explore these measurement characteristics and analytical variable reduction techniques. The final study aims to use these data reduction approaches to examine relationships between meaningful CMJ variables and cumulative training load. The specific aims, hypotheses, and significance of each study/chapter are briefly outlined below.

1.3.1. Methods Section (Chapter 3): Using measurement characteristics to select CMJ kinetic variables for use in longitudinal monitoring: A technical report

Aim: This report aims to detail a decision-making framework for selecting a manageable number of CMJ variables to enhance athlete monitoring. This is in an effort to improve the precision and practical utility of athlete monitoring systems by addressing challenges such as inconsistent calculation methods, varied nomenclature, and arbitrary selection criteria, thus providing clarity and standardisation in data interpretation. Ultimately, the report aims to contribute to sports science by offering a replicable model for future research and a practical model that improves the ability of practitioners to make informed training decisions to optimise athletic performance.

Process: The process begins with focusing on essential measurement characteristics—reliability, sensitivity, and covariance—to refine CMJ variable selection methodologies. Reliability is assessed through relative reliability (intra-class correlation coefficient) and absolute reliability (typical error of measurement). Sensitivity, measured by the signal-to-noise ratio (SNR), evaluates the responsiveness of outcome measures to stimuli. Co-variance analysis, particularly principal component analysis (PCA), identifies correlations between variables, aiding in data reduction. The systematic approach includes steps such as establishing noise (absolute test/re-test reliability and week-to-week variation), finding the signal (longitudinal SNR), removing noise (PCA for co-variance analysis), and selecting variables (based on highest SNR). Applied to a case study involving professional rugby union players, this approach effectively identifies sensitive CMJ variables indicative of neuromuscular performance.

1.3.2. *Study 1 (Chapter 4): Establishing the noise: inter-day ecological reliability of countermovement jump variables in professional rugby union player*s

Aims: This study aimed to examine the inter-day reliability of a wide range of CMJ kinetic variables, using 'ecologically valid' and widely applicable assessment protocols, in professional rugby union players.

Significance: Through the examination of reliability of different data treatment methods (i.e., the use of the average of 3 jumps or a single best jump for CMJ variable results) *Study 1* adds insight to the practical application of CMJ variable data in a team setting. Absolute reliability provides a measure of the normal methodological and biological variation expected in each measure (Atkinson & Nevill, 1998), an important understanding for practitioners when evaluating whether changes are 'real', or within normal variation. Despite the widespread use of the CMJ in monitoring of athletes, few reliability studies have been conducted in highly trained populations (i.e., professional athletes with training age ~ 5 years) (Cormack, Newton, Mcguigan, et al., 2008a; Ryan et al., 2019a; Thorpe et al., 2015). Well controlled reliability studies typically collect data over 2-3 days of testing without any substantial training between each testing day, experimental conditions achievable with university students or recreational athletes in laboratory-based studies. These conditions are, however, generally not feasible with professional athletes, as it would require disruption of normal training routines. This issue was addressed in professional soccer by evaluating players over 2 consecutive days, with the first a day prior to the start of pre-season (Thorpe, 2018). This study demonstrates that such stringent testing conditions may not be necessary, with any combination of 2 days within the first week of pre-season provides similar results for absolute and relative reliability .

1.3.3. Study 2 (Chapter 5): Sensitivity of countermovement jump variables in professional rugby union players within a playing season

*Aims**:*** This study aims to calculate the signal to noise ratio (SNR) of a wide range of CMJ variables to determine their sensitivity to the training and competition undertaken by professional rugby union players throughout a season. A secondary aim is to compare the sensitivity calculated using 3 different data treatment methods.

Significance: *Study 2* provides further information on practical methodologies that can be employed by practitioners to better understand CMJ variable measurement characteristics within their specific cohort(s). Understanding the expected week-to-week variation ("signal") of each CMJ measure in relation to the normal methodological and biological variation ("noise") is a way of characterising the likelihood of a CMJ variable to change in response to training and game stimuli. While inter-day reliability is commonly reported, there is a paucity of information exploring this measurement characteristic in the context of season variability, to better understand measurement sensitivity. Additionally, typical CMJ assessment protocols in monitoring involve the athlete performing multiple trials. As such, the practitioner must determine whether to examine a single jump (e.g., 'best' trial), or the mean of multiple trials. This is an important data treatment decision which may impact the interpretation of results as it has been shown to produce differing inter-day reliability of variables (Howarth et al., 2021).

1.3.4. *Study 3 (Chapter 6): Reducing* the noise: an agnostic approach to data reduction for monitoring changes in countermovement jump kinetic variables

Aim: This study aims to comprehensively explore CMJ variable covariance, using a series of principal component analyses (PCA) on phase grouped variables from assessments of professional rugby union players. This method is proposed as a means of assisting practitioners to highlight potential redundancies in the use of highly correlated variables for longitudinal monitoring.

Significance: *Study 3* provides a novel approach to selecting a smaller set of variables for practitioners to monitor throughout a season, without relying on generalised findings from other athlete groups or subjective opinions about the usefulness of particular variables. Previous research has reduced variables using a priori criteria, such as pre-selecting only those variables that have been commonly researched (James et al., 2021), using variables that, based on subjective assumptions, will improve model validity (Merrigan, Rentz, et al., 2021), or those that have sufficient reliability (e.g., CV ≤10%)(Anicic et al., 2023). Each of these 'guided' approaches, involving the pre-selection of a variable subset, is problematic due to their reliance on arbitrary inclusion criteria. To overcome this limitation, an initial step of simplifying the variable pool to align with the primary focus of the investigation (e.g., only analysing bilateral variables when measuring neuromuscular fatigue by removing asymmetries and single leg values) (Howarth et al., 2021) will effectively reduce the number of variables. A further practical solution is to separate CMJ variables into phase groupings (i.e., eccentric/downward, concentric/upward, landing). This method enables performing separate PCAs on these smaller groups of variables (that is, fewer variables in each PCA compared to the number of players), while still including all available variables in the analysis. In turn, this study represents the most comprehensive examination of covariance using PCA to explore the results of professional rugby union players.

1.3.5. *Study 4 (Chapter 7):* Neuromuscular response to training load in professional rugby union players

Aim: This study aims to elucidate the effects of cumulative training and game workloads on neuromuscular function in professional rugby union players. Specifically, that different cumulative loads would have different neuromuscular effects (i.e., different variables affected) depending on when the measures were taken in the weekly training cycle (i.e., <72 hours post-game, or >96 hours post-game).

Significance: *Study 4* highlights findings that are important for practitioners' planning of training and recovery. Dividing the assessment into two constructs (i.e., <72 hours post-game, or >96 hours post-game) allows for deeper investigation into the bimodal pattern of neuromuscular recovery (Nicol et al., 2006), while concurrently examining timeframes for load accumulation that correspond to those of interest to practitioners (i.e., 3-, 7-, and 28-day cumulative loads) (Gabbett, 2016). This study not only addresses a gap in the current literature by examining these relationships within professional rugby but also paves the way for future research to apply similar methods in other team sports. By employing a comprehensive approach that integrates GPS tracking, resistance training volume, and session rate of perceived exertion (sRPE) load, this research provides a robust framework for understanding how different types of training stimuli impact neuromuscular function. The findings offer critical insights into the temporal dynamics of neuromuscular fatigue and recovery, emphasising the need for individualised training load management to optimise performance and minimise injury risk.

Chapter 2

From theory to field: A narrative review of the measurement of neuromuscular status for rugby union

2.1. Planning for physical adaptation in team sports

Physical adaptation in athletes, especially in field sports, is a complex process that necessitates strategic planning and execution of training programs to achieve optimal performance. ‘Periodised’ training plans are designed to systematically structure training intensity, volume, and modality across different periods or phases to maximise adaptation and minimise the risk of overtraining and injuries. These plans are rooted in the principle of progressive overload, where the body is gradually exposed to increased stress to stimulate adaptation, thereby improving athletic performance over time. The science underpinning periodised training is well-established, with seminal works by Bompa (Bompa & Haff, 2009) and Issurin (Issurin, 2010) highlighting its effectiveness in enhancing individual athletic performance by carefully managing workload and recovery cycles. However, the demand of professional team sports seasons requires the athletes involved to engage in ‘concurrent’ physical preparation, whereby several aspects of their physical performance are being developed at the same time (Jones et al., 2016; Nader, 2006; Wilson et al., 2012). Concurrent training presents a unique challenge within periodised training frameworks due to the competing demands of strength, endurance, and skill adaptations (Hickson, 1980), but is the best solution given the game and training schedules of professional team sports (Kiely, 2012).

The efficacy and optimisation of concurrent training are subjects of ongoing research, with studies suggesting that strategic sequencing and balancing of training modalities can mitigate potential interference effects on adaptation (Hickson, 1980; Wilson et al., 2012). The interference phenomenon (Hickson, 1980), indicates that simultaneous endurance and strength training may impair strength gains compared to when strength training is performed in isolation. This has led to nuanced strategies to optimise concurrent training outcomes, including the manipulation of training volume, intensity, and the timing of strength and endurance sessions (Hennessy & Watson, 1994; Kiely, 2012; Murach & Bagley, 2016). Recent research suggests that the interference effect might be more nuanced than previously thought, with factors such as training history, athlete genetics, and the specificity of the training stimulus playing significant roles (Murach & Bagley, 2016). To maximise the benefits of concurrent training in field sports, periodised plans often incorporate varied training intensities and volumes tailored to the athlete's competitive calendar, ensuring that adaptations are timed to peak at critical points in the season (Halson, 2014). This strategic approach allows for the concurrent development of endurance, strength, and sport-specific skills, providing a comprehensive conditioning base for athletes (Murach & Bagley, 2016). Harmonising the development of endurance, strength, and sport-specific skills requires an understanding of the cumulative acute and chronic responses to concurrent training stimuli (Kiely, 2012; Murach & Bagley, 2016).

2.1.1. Adaptation to training stimulus

Quantifying the training load and subsequent response to exercise interventions within certain timeframes is a well-established concept in sport and exercise science, with dose-response relationships being of perennial interest to researchers (Coutts et al., 2018; Ellis et al., 2022; Malone et al., 2018). Indeed, the timeframe for investigating the dose-response relationship can be set according to the expected residual fatigue or adaptation times for a certain stimulus (Sysler & Stull, 1970). In this way, the researcher or practitioner can understand more deeply the possible interruption or adaptation an athlete can expect to encounter through training and within the context of their training cycle or season (Coutts et al., 2018). The timeframe for quantifying an ‘acute’ training stimulus is typically one ‘micro-cycle’ (3-7 days) (Bompa & Haff, 2009), with acute responses referring to the immediate physiological and psychological effects following that time (Carling et al., 2018; Da Silva et al., 2020). These responses include muscle fatigue, hormonal changes, and psychological stress (Enoka & Duchateau, 2016). 'Chronic' timeframes are those that look to evaluate a longer-term residual effect of training efficacy or fatigue, usually encompassing either a 'meso-cycle' or training phase (4-20 weeks) (Bompa & Haff, 2009). Chronic responses, then, denote longer-term adaptations that occur from repeated exposure to training stimuli, including improvements in muscular strength, aerobic capacity, and skill proficiency (Cormie et al., 2011a, 2011b; Laursen & Jenkins, 2002). The concept of the fitness-fatigue paradigm, as outlined by Calvert et al. (Calvert et al., 1976), provides a framework to understand how the balance between acute and chronic load-response relationships can influence performance, with the cumulative training load playing a crucial role in dictating this balance over the course of a season (Coutts et al., 2018).

Monitoring training loads is helpful in this context, serving as a strategy to optimise the balance between achieving desired adaptations and preventing overtraining or injury. Training load is quantified through various metrics, including session rate of perceived exertion (sRPE), total distance covered, and physiological measures such as heart rate variability (Halson, 2014). These metrics offer insights into the workload imposed on athletes, enabling practitioners to make informed decisions regarding training intensity, volume, and recovery in the context of the expected responses to training. The integration of technology, such as wearable sensors and GPS tracking, has significantly enhanced the precision of monitoring (Howe et al., 2020; Young et al., 2012), allowing for a detailed analysis of the athlete's responses to training stimuli across different physiological systems. Such an approach ensures that the cumulative effects of training load are aligned with the athlete's capacity for recovery.

2.1.2. *Game demands*

Each sport has its own set of unique physical demands (Gabbett et al., 2013; Lopategui et al., 2021; Taberner et al., 2020; Thorpe et al., 2017), which can vary within each support depending on the position played (Austin & Kelly, 2013; Tee et al., 2017), competition played in (Austin et al., 2011; McLean, 1992; Quarrie et al., 2013; Roberts et al., 2008), and even the specific opposition being played against (Quarrie & Hopkins, 2007). These demands determine the types and balance of application of training and recovery strategies that practitioners might use to best prepare their athletes (Thorpe et al., 2017; Varley et al., 2017).

2.1.2.1. *Running load*

Field-based sports such as rugby union, rugby league, Australian rules football, and soccer impose distinctive training demands on athletes, characterised by the need for high levels of aerobic fitness, strength, speed, and sport-specific tactical skills (Cunniffe et al., 2009; Fornasier-Santos et al., 2021; Tee et al., 2017; Young et al., 2012). These sports require athletes to cover substantial distances during a game, with soccer players averaging 10-12 km, Australian rules footballers 12-20 km, and rugby players 5-7 km, depending on their position and the specific dynamics of the game (Bangsbo et al., 1991; Cormack et al., 2013; Deutsch et al., 1998). Within these distances, the volumes of high-speed running (HSR) and very high-speed running (VHSR) are critical metrics for understanding the physical demands placed on athletes. For instance, soccer players can perform up to 2.5 km of HSR (>5.5 m/sec) and 250-700 m of VHSR (> 6.5 m/sec) per match, indicating the significant contribution of the anaerobic energy system (Bangsbo et al., 1991). The acute effects of these high-intensity efforts include marked increases in muscle fatigue and metabolic stress (Cormack, Newton, & McGuigan, 2008; McLean et al., 2010; Shearer et al., 2015), while the chronic adaptations can lead to enhancements in aerobic capacity (maximal oxygen consumption - VO2 max), muscle endurance, and sprint speed (Bishop et al., 2011; Roe, Darrall-Jones, et al., 2016), directly influencing athletes' performance capabilities and resilience to fatigue over the course of a season.

2.1.2.2. Speed and power

Speed and power are pivotal attributes in field-based sports, where they significantly contribute to key moments of the game, including sprinting, jumping, and rapid changes of direction. These qualities not only facilitate performance in high-intensity actions but are also crucial for creating and exploiting opportunities in attack and for effective defence (Bishop et al., 2011; Young et al., 2012). In rugby union, for instance, the ability to rapidly accelerate and apply force in tackles can determine the outcome of crucial game moments (McLean, 1992). Similarly, in soccer, the capacity to sprint and change direction swiftly is essential for breaking defensive lines and creating scoring opportunities (de Hoyo et al., 2016). Power, often measured by an athlete's ability to perform explosive movements such as jumps or sprints, is directly related to muscle strength and neuromuscular coordination (Cormie et al., 2011a, 2011b). The importance of these attributes across different field sports is underscored by the correlation between measures of speed and power with game-related performance indicators (Bishop et al., 2011; Cronin & Hansen, 2005; Young et al., 2011).

Development of speed and power is achieved through chronic adaptation (i.e., across a meso- or macro-cycle) to specific stimuli (Cormie et al., 2011b). However, continuing to develop or, indeed, maintain these qualities throughout the competitive season presents significant challenges for athletes, primarily due to the competing demands posed by running volumes and intensities encountered (Crowcroft et al., 2015; Wilson et al., 2012). The accumulation of fatigue from competition and training can impair neuromuscular function, reducing an athlete's ability to perform high-intensity efforts and potentially leading to a decline in speed and power-related performance (Cormack et al., 2013).

2.1.3. Physiological effects

The combined game and training demands elicit specific physical and physiological responses from all the systems of the human body. The complex and sometimes conflicting interactions and fluctuations of systems of the human body can impact sporting performance, presenting a complex management challenge for those working with athletes (Behrens et al., 2023; Jeffries et al., 2021).

2.1.3.1. Physiological systems

The human body operates through the complex integration of several different systems. Regarding sports performance, the predominant systems are the cardiovascular, respiratory, skeletal, endocrine, digestive, immune, and neuromuscular systems (Behrens et al., 2023). As an example of this, take the complex interplay between the cardiovascular, respiratory, and endocrine systems. The cardiovascular system's role in delivering oxygen and nutrients optimises endurance and performance (Joyner & Coyle, 2008), facilitated by the respiratory system's effective gas exchange and regulation of acid-base balance (Sheel, 2002; Wagner, 1996). Concurrently, the endocrine system modulates these processes through hormonal regulation of energy metabolism, recovery, and physical stress adaptation, influencing both cardiovascular efficiency and respiratory function (Crewther et al., 2006; Viru, 2001). This intricate interrelationship ensures that athletes can maintain performance at optimal levels under the rigorous demands of competitive sports.

Given the relationship speed and power has to the sport specific demands of field sports, the responses of the neuromuscular system have been important to quantify for practitioners in field sports (Cormack, Newton, & McGuigan, 2008; Cormack, Newton, McGuigan, & Cormie, 2008; McLean et al., 2010; Norris et al., 2021a; Oliver et al., 2015; Overton, 2013; Place & Millet, 2020). To best understand these changes in other complex interactions within the bodies of athletes when they perform, a deeper understanding of neuromuscular physiology is needed.

2.2. Neuromuscular status

The term "neuromuscular status" is often used to refer to the current condition of an athlete's neuromuscular system, reflected in their “motor performance” (Behrens et al., 2023), including their muscle strength, power output, and coordination. Neuromuscular status is dynamic, existing on a continuum of “performance fatiguability” (Behrens et al., 2023; Enoka & Duchateau, 2016) between heightened fitness and fatigue in response to training loads and recovery processes (Coutts et al., 2018). Human neuromuscular anatomy involves the complex interplay between the nervous system and the muscular system, which enables the initiation and control of muscle contractions, thereby facilitating movement. This system is primarily composed of motor neurons, neuromuscular junctions, and skeletal muscle fibres (Shepherd, 1994). Motor neurons, originating in the spinal cord, extend their axons to muscle fibres, forming a connection at the neuromuscular junction, a specialised synapse designed to transmit nerve impulses to the muscle (Shepherd, 1994). These impulses trigger a cascade of events leading to the sliding of actin and myosin filaments within the muscle fibres, resulting in contraction. Skeletal muscles, characterised by their striated appearance due to the organised arrangement of these filaments, are under voluntary control, governed by the central and peripheral nervous systems (Shepherd, 1994).

2.2.1. Central Nervous System (CNS)

The physiology of the central nervous system (CNS) is fundamental to understanding its role in neuromuscular function and, by extension, sports performance. The brain and spinal cord make up the CNS, which coordinates voluntary movements through a complex integration of sensory inputs, motor planning, and execution of motor commands (Purves & Williams, 2001). Motor commands are generated in the motor cortex and transmitted through descending pathways to the spinal cord, where they synapse with motor neurons (Purves & Williams, 2001). These neurons innervate skeletal muscles, triggering contractions that result in movement. This intricate process is modulated by various brain regions, including the basal ganglia and cerebellum, which play critical roles in the regulation of movement precision, balance, and coordination (Purves & Williams, 2001). The capacity for rapid, forceful, and accurate movements is significantly influenced by the efficiency of neural pathways. The CNS is essential in this regard, as it governs the ability to process and integrate sensory information, thereby enabling the instantaneous adaptation and fine-tuning of motor output—meaning the CNS plays a critical role in sports performance.(Purves & Williams, 2001; Shepherd, 1994).
Furthermore, the CNS's role in neuromuscular function extends to the adaptation mechanisms following consistent training, highlighting its capacity for neuroplasticity in response to physical activity (Wolpaw & Tennissen, 2001). Through a process known as motor learning, repeated practice of specific movements results in the refinement of neural circuits involved in those movements, leading to improvements in strength, speed, and coordination—key components of sports performance (Wolpaw & Tennissen, 2001). Rate coding refers to the frequency of nerve impulse transmission from the CNS to muscle fibres (Duchateau & Enoka, 2011), further modulating force production. As the intensity of an activity increases, the firing rate of motor neurons escalates, allowing for greater muscle tension and faster, more powerful

movements (Enoka & Duchateau, 2008). This is especially important in sports requiring rapid changes in speed and direction, where the ability to quickly generate high force levels can distinguish between successful and unsuccessful performance outcomes (Enoka & Duchateau, 2008; Gandevia, 2001). For example, in field sports, the ability to execute powerful sprints, make rapid changes of direction, and sustain high-intensity efforts throughout a game are critical to successful performance (Cronin & Hansen, 2005; Lacome et al., 2014; Roberts et al., 2008; Taberner et al., 2020; Young et al., 2012). Training regimens that focus on neuromuscular efficiency, including plyometrics and resistance training, can enhance these physiological attributes (Aagaard, 2003; Aagaard et al., 2002; Sale, 1988), leading to improved performance on the field.

2.2.2. Peripheral Nervous System (PNS)

The PNS comprises nerves and ganglia outside of the brain and spinal cord, including those responsible for conveying motor commands to skeletal muscles (Purves & Williams, 2001). Motor unit recruitment, a key physiological process within the PNS, involves the activation of motor units—a motor neuron and the skeletal muscle fibres it innervates—to produce muscle contractions (Shepherd, 1994). The size principle asserts that motor units are activated on the basis of their size; smaller ones are recruited first, followed by larger ones.(Henneman, 1957). This recruitment pattern is related to the threshold level of stimulation required to activate different motor units. Smaller motor units, which have smaller, more excitable motor neurons, are easier to depolarise and are activated with weaker neural stimuli. They are responsible for smaller, precise movements and can be activated for long periods without fatigue. As the intensity of muscle contraction increases, larger motor units with larger, less excitable motor neurons are recruited. These larger units generate more force but are less resistant to fatigue compared to smaller motor units. The size principle ensures that muscles can engage in a gradated response to different demands, from light to heavy loads, allowing for energy efficiency and the ability to produce varying degrees of force as needed. (Enoka & Duchateau, 2008; Henneman, 1957).

An essential function of the peripheral nervous system that enhances neuromuscular efficiency and performance is motor unit synchronisation. Synchronisation refers to the temporal coordination of motor unit activation, which can increase the force output of muscles during synchronous activities (Gandevia, 2001), critical for explosive movements like sprinting or jumping in field sports. This adaptation is mediated by changes at the synaptic level, including the efficiency of neurotransmitter release and the strength of synaptic connections, facilitating more effective motor unit recruitment and synchronisation (Gandevia, 2001). Consequently, athletes can achieve enhanced performance not only through muscular adaptations but also through optimised neuromuscular coordination (Gandevia, 2001). This underscores the importance of incorporating skill-specific drills and neuromuscular training into athletic preparation to leverage the PNS's adaptability for peak performance (Gandevia, 2001; Wolpaw & Tennissen, 2001).

2.2.3. Stretch Shortening Cycle (SSC)

Movements that incorporate the stretch shortening cycle (SSC) are those incorporating a rapid eccentric contraction (i.e., muscle lengthens under tension) and is immediately followed by a concentric contraction (i.e., muscle shortens) (Komi & Bosco, 1978). The efficiency and output of the SSC are described as the combination of two overarching mechanisms – the “neuromuscular model”, and the “mechanical model”(Król & Mynarski, 2012). The “neuromuscular model” is primarily based on the stretch reflex, governed by the muscle spindle providing information to the central nervous system on the velocity of change in muscle length. When a muscle lengthens rapidly, the CNS responds by sending an opposing signal, via alpha motor neurons, for it to contract (Król & Mynarski, 2012). The neuromuscular model suggests a 'potentiation' effect generated by pre-loading, which creates an excitatory neural stimulus for greater contraction force during the following concentric contraction. The "mechanical model" is based on the elastic capacity of the muscle-tendon complex (Król & Mynarski, 2012). The muscle-tendon complex, made up of both contractile and non-contractile elements, returns rapidly to shape after it is stretched by an external force. The contractile elements are contained within the sarcomere (actin and myosin), while the non-contractile elements are made up of the series elastic component (also known as the musculotendinous unit) and the parallel elastic component (connective tissues, muscle bundles and the whole muscle itself) (Król & Mynarski, 2012). The mechanical model suggests that if an eccentric force is followed rapidly by a concentric force, the 'rebounding' series elastic component will contribute additional force to the concentric contraction forces (Komi & Bosco, 1978; Komi, 1984). Movements that rely on the use of the SSC are, therefore, useful for understanding the current state and function of the neuromuscular system due to their ability to expose changes in neuromechanical proficiency including reductions in voluntary contraction levels, twitch response, and coordination (Nicol et al., 2006). Indeed, the more information that can be gathered when performing these movements, the more likely practitioners and researchers are to be able to quantify changes arising from central and peripheral mechanisms (Gandevia, 2001; Nicol et al., 2006).

2.2.4. Measuring neuromuscular function

In 1920, The Lancet published an article by Wing Commander Martin Flack of The Royal Air Force detailing the medical requirements of Air Navigation (Flack, 1920). To evaluate a pilot's readiness to undertake training and perform, Flack outlined ‘Tests of Neuromuscular Coordination and Nervous Stability’ (Flack, 1920). The battery of tests included single leg balance, the ability to lift a rod squarely with one arm and replace it, tremor of the eyes, tongue and hands, and a knee-jerk test. The results of this testing found that those who were ranked in the higher levels of neuromuscular coordination and nervous stability were more likely to pass flying training and “gain their wings” (Flack, 1920). Numerous tests have since been proposed to aid in the assessment of neuromuscular status. These tests have been integrated into other arenas outside of military service to assess readiness, particularly in sports (Abernethy et al., 1995; Binder-Macleod & Snyder-Mackler, 1993; Enoka & Stuart, 1992; Stokes & Dalton, 1991). Additionally, an effort to better quantify the results of these tests has included the use of advanced measurement equipment. Devices such as high-speed camera systems, electromyography (EMG), isokinetic dynamometers, accelerometers, timing devices, and force transducers have been used to measure the kinetic outputs of movement (Binder-Macleod & Snyder-Mackler, 1993; Fowles, 2006; Impellizzeri et al., 2007; Stokes & Dalton, 1991).

Many tests of neuromuscular status require complex equipment and lengthy or stressful protocols (Fowles, 2006). EMG is an example of this. As an accessible measure of the electrical activity arising from motor unit recruitment, it has meant that it is a highly cited tool for investigating neuromuscular function in fatigued states or competition periods (Arnal et al., 2016; Boccia et al., 2015; Brandon et al., 2015; Conceição et al., 2014; Duhig et al., 2017; Edwards & Hyde, 1977; Hébert-Losier et al., 2017; Minshull et al., 2012; Miramonti et al., 2016; Raeder et al., 2016; Stutzig & Siebert, 2017; Wojtys et al., 1996; Zebis et al., 2011).. While many options exist for assessing neuromuscular status in a lab setting, the practicality of implementing these tests is a confounding factor in the elite sports environment. One tool that has been utilised in lab studies and practical environments is the countermovement jump

(Johnston et al., 2014; Padulo et al., 2017; Pareja-Blanco et al., 2017; Raeder et al., 2016; Shearer et al., 2015; Shearer et al., 2017; Silva et al., 2013; Silva et al., 2018; Watkins et al., 2017). The following sections will discuss the CMJ in detail, as this is one of the most common tools used in team sports.

2.3. Countermovement Jump (CMJ)

Shortly following Flack's 1920 article (Flack, 1920), Dudley Sargent proposed the maximum vertical jump as "The physical test of a man" (Sargent, 1921) under the premise that gravity is 'one of the strongest natural forces with which man is constantly contending". The subjects performed a countermovement jump, first lowering themselves to a self-selected depth (the countermovement) and then, without pause, propelled themselves upward with maximal effort, attempting to touch the top of their head to a cardboard disk suspended to a specific height (Sargent, 1921). The resultant jump heights were then added to formulae that used the subjects' weight and height to estimate work in foot-pounds as a measure of jump 'efficiency', and an index of jump height to standing height, as comparative measures (Sargent, 1921), thus allowing the comparison of each subject on relative power production.

Performing a CMJ inherently incorporates the stretch shortening cycle, and, due to the speed of movement, allows evaluation of several phases of movement (Hennessy & Kilty, 2001; Sahrom et al., 2020; Sole et al., 2018). A CMJ takes around 600-1000ms to perform, typically of which approximately 380ms is downward movement (also called the eccentric phase, which is the countermovement) and approximately 400ms is upward movement (also called the concentric phase) (Gathercole, Stellingwerff, et al., 2015a). Other jump tests have been proposed to evaluate the lower body stretch-shortening cycle, such as the depth jump. The approximate total contact time of the depth jump is ~200 ms (eccentric and concentric phases combined). The duration of a CMJ affords the practitioner a larger sample from which to evaluate key aspects of the SSC and help to clearly define where deficits in the SSC may exist (Sole et al., 2018). Indeed, this allows investigation of both the 'slower' muscular contributions to the SSC, and the interaction between neural and mechanical factors seen in the shorter timeframes (Hennessy & Kilty, 2001). Therefore, variables that can be reliably measured across individuals and groups could be used to quantify specific changes in neuromuscular status arising from training.

2.3.1. Relevance of the CMJ

Validity assesses the degree to which a test measures what it purports to measure (*Standards for Educational and Psychological Testing*, 1999). Recently, unified validity theory has been proposed by Windt et al. (Windt et al., 2019), suggesting an integrated approach to understanding validity, viewing it as a singular, multifaceted concept rather than distinguishing between different types of validity (construct, criterion, and content). Unified validity theory emphasises the importance of evaluating evidence from various sources to assess the overall validity of a test (Windt et al., 2019). The most important outcome of measuring validity, according to this perspective, is to ensure that a test is genuinely useful for monitoring athletes, thereby enhancing the practical application of effective monitoring strategies (Windt et al., 2019). With these criteria in mind, we can evaluate the validity of the CMJ as an assessment. Simple measurement equipment such as the Vertec (Vertec Jump, Carson, CA, United States), is often used to assess jump height (Cormie et al., 2011a, 2011b; Cronin & Hansen, 2005; Focke et al., 2013) and it has been included as a measure of specific performance and power in testing batteries for sporting combine events, specifically in the National Football League (NFL) and National Basketball Association (NBA). CMJ performance has been shown to correlate well with other dynamic tasks, such as sprint performance and repeat sprint ability

(Buchheit et al., 2010; Markström & Olsson, 2013; Misjuk & Viru, 2007). Investigations of the relationship between sprint speed and CMJ performance (i.e., jump height and peak power) in elite sprinters, demonstrate strong (r =-0.49 to -0.53) (Misjuk & Viru, 2007) to very-strong (R^2 = 0.79 – 0.83) (Markström & Olsson, 2013) relationships. Correlations between jump height and speed are also evident in field- and court-sport athletes. A study of 26 male rugby league players (Cronin & Hansen, 2005) found a strong relationship between the CMJ height and sprint (r = -0.56 to -0.66), as did an investigation of 186 mixed-gender soccer and basketball athletes (r = -0.52 to -0.92) (Rodríguez-Rosell et al., 2017). Notably, these studies show correlation of similar magnitudes, despite the diverse populations examined. The consistency with which these strong correlations between CMJ and speed performance are seen in all athletes indicates that the CMJ is a good indicator of an athlete's ability to create lower extremity power and impulse not only in the specific task of jumping, but in other ballistic tasks utilising the SSC (Cronin & Hansen, 2005). These findings are indicative of the overall validity of the CMJ as a test of neuromuscular status.

2.3.2. Measuring the CMJ

Force platforms are biomechanical devices designed to measure the ground reaction forces generated by a body standing or moving across them, providing essential data for analysing physical interactions with the ground during various activities, including the CMJ (Linthorne, 2001; Richter et al., 2014a). Over time, force platform systems have become more readily available for use with athletes. With their prominence, so too have the number of analyses available and their accessibility through bespoke software packages (Bishop et al., 2023; Bishop et al., 2021). Indeed, lower price points for systems along with instantaneous calculation of myriad variables, has allowed more in-depth examination of CMJ metrics. Foundational research in this area from Cormie et.al. investigated a wide range of variables using time relative information from force, velocity and power data coming from CMJs performed on a force platform by Division I collegiate athletes (Cormie et al., 2009b). A primary aim of the study was to characterise the differences between 'jumpers' (defined as those with a maximum jump height > 50cm) and 'non-jumpers' (defined as those with a maximum jump height < 50cm) (Cormie et al., 2009b). Significant differences were noted in several variables between the groups, with 'jumpers' creating greater peak power, concentric peak force, eccentric peak force, peak velocity, concentric rate of power development, force at peak power, velocity at peak power, acceleration, and total work. Additionally, significantly larger area within the force-velocity loop was noted, demonstrating that 'jumpers' employ a strategy that allows greater creation of force at higher velocities, underpinning the results seen for the discrete variables mentioned (Cormie et al., 2009b).

2.3.3. Foundational research using the CMJ as a measure of neuromuscular status

Research investigating how jump performance and the stretch-shortening cycle is affected by resistance training and fatigue has begun to elucidate the utility of CMJ testing for athletes (Cormack et al., 2013; Cormack, Newton, & McGuigan, 2008; Cormack, Newton, McGuigan, & Cormie, 2008; Cormack, Newton, Mcguigan, et al., 2008a; Cormie et al., 2009b; Gathercole, Stellingwerff, et al., 2015b; Gathercole, Sporer, et al., 2015a; Kennedy & Drake, 2018). An example of this is seen following the initial evaluation comparing 'jumpers' and 'non-jumpers' by Cormie et.al., where differences in the response of CMJ metrics were investigated between those groups, following a 12-week power focused training program (Cormie et al., 2009b). A unique finding of this study was that concentric rate of power development, acceleration, and force at peak power all differed between 'jumpers' and 'non-jumpers' but were not responsive to the training intervention (Cormie et al., 2009b). This could suggest that these variables are more indicative of the innate capacity of those athletes (e.g. the ability to create high rates of power development is an innate quality of a 'jumper'). Conversely, area within the force-velocity loop (W/kg) and velocity at peak power (m/s) showed significant improvement in both groups from the training, suggesting that these kinetic properties are the ones being trained in the program (Cormie et al., 2009b). The importance of the role of strength and power training for improved athletic performance is well established (Cormie et al., 2011b) but not universally well understood (Cormie et al., 2011a). Feedback such as this data can help practitioners to better target training interventions for optimal athletic outcomes (Aagaard, 2003). The role of fatigue on CMJ metrics is another area of interest, that Gathercole et.al. examined (Gathercole, Sporer, et al., 2015a). Following repeated Yo-Yo intermittent recovery and 20m sprint tests, the investigators noted increases in eccentric, concentric, and overall duration in the subjects' CMJ, alongside a decrease in mean eccentric and concentric power for 72 hours (Gathercole, Sporer, et al., 2015a). The authors proposed that such changes are indicative of 'low frequency fatigue,' defined as persistent decrements in contractile function after the restoration of acute metabolic fatigue (Gathercole, Sporer, et al., 2015a). The variables examined offer unique insights to the strategy each athlete uses for the jump (e.g., timing and intent in pre-loading/countermovement) (Sole et al., 2018).

The findings of Cormie et.al. (Cormie et al., 2009b) and Gathercole et.al. (Gathercole, Sporer, et al., 2015a) indicate the value of utilising CMJ metrics to monitor change in the neuromuscular performance of athletes. However, the practical utilisation of the CMJ test in an evidence-based framework is an essential test of ecological validity (Coutts, 2017). Cormack et. al. focused on the acute responses of 22 elite level players to an Australian Rules Football (ARF) match (Cormack, Newton, & McGuigan, 2008). The CMJ was tested 48 hours pre-, immediately pre-, immediately post-, 24 hours post-, 72 hours post-, 96 hours post-, and 120 hours post- match. To examine which CMJ variables were significantly affected by the match, analysis was limited to those variables with effect size of >0.40 (immediately pre- to immediately post-match). The variables used included flight time, mean power, relative mean power, relative mean force, and flight time: contraction time ratio (FTCT). Of these, FTCT proved to be most sensitive in assessing the time-course of fatigue, as evidenced by a substantial decrease immediately post- x -0.65 ±0.28, 90%CI) and 24 hours post-match (ES -0.67 ±0.28, 90%CI), before returning to trivial difference at 72 hours post-match (Cormack, Newton, & McGuigan, 2008). This led the authors to conclude that this is the average timeline of neuromuscular performance recovery, following AFL competition (Cormack, Newton, & McGuigan, 2008). Variation in the magnitude of fatigue and timeline of recovery between athletes indicates the individuality of response to the demands of the game. Such variation between athletes is intuitive when considering differing positional demands and individual training status, further demonstrating the value of FTCT as an individual monitoring variable in an applied setting.

2.3.3.1. Reliability

Reliability is a crucial measurement characteristic of a test, referring to the consistency and repeatability of test scores across different administrations under similar conditions (Atkinson & Nevill, 1998). Various types of reliability can be measured, including test-retest reliability, which assesses the stability of a test over time (Atkinson & Nevill, 1998). From this, absolute reliability can be used to established through the typical error of measurement (Hopkins, 2000). This value is expressed as a coefficient of variation (CV%) (Hopkins, 2000), indicating the expected percentage of variation each test variable would have owing to the testing methods or day-to-day human fluctuation. The most important outcome of measuring reliability is to ensure the utility of a test or variable for monitoring athletes by providing confidence in the consistency and precision of the measurements obtained, thereby supporting effective decision-making in athlete training and performance monitoring (Atkinson & Nevill, 1998).

Although the investigation of change in CMJ metrics demonstrates a ‘significant response’ (Cormack, Newton, & McGuigan, 2008) from the neuromuscular system to stimulus, there is still a need to understand this important measurement characteristics (Coutts, 2014). The investigations of CMJ variable response to matches by Cormack et al (Cormack et al., 2013; Cormack, Newton, & McGuigan, 2008; Cormack, Newton, McGuigan, & Cormie, 2008) were preceded by a reliability study (Cormack, Newton, Mcguigan, et al., 2008a) examining 16 variables for both intra- and inter-day reliability. Of these 16 variables, 10 met inclusion criteria set by the authors, which was a combined (averaged) intra-day and inter-day CV <10%. FTCT met the criteria, averaging 8.2% (intra-day CV = 6.1%; inter-day CV = 10.4%). This was the least reliable CMJ variable in the study(Cormack, Newton, Mcguigan, et al., 2008a). However, such arbitrary criteria could exclude variables from further study that are important for understanding jump strategy (Gathercole, Sporer, et al., 2015b) and may indeed be sensitive to change as the ongoing results vary more than the typical error of measurement(Kraufvelin, 1998).

2.3.3.2. Sensitivity

Sensitivity as a measurement characteristic refers to a test's ability to accurately detect changes in the variable it measures, especially small but meaningful changes that can indicate progress or the need for adjustment in an athlete's training program. The sensitivity of a testing variable is measured using a signal to noise ratio, whereby the response of that variable to a particular stimulus is divided by a critical value for ‘normal variation’, such as the smallest worthwhile change (0.2 x the between subject standard deviation) (Currell & Jeukendrup, 2008; Edwards et al., 2018a). A signal to noise ratio of >1.0 would indicate a change that exceeds the critical value (Currell & Jeukendrup, 2008).

Previous research into the sensitivity of CMJ have found that several metrics, such as jump height, mean force, relative peak power, mean power, and peak power, meet this criterion (Kennedy & Drake, 2018). However, these SNR findings do not tell the full story of sensitivity, as they do not account for the significance of the change. For example, Gathercole et.al. (Gathercole, Stellingwerff, et al., 2015b) found that while these measures could be categorised as ‘sensitive’, peak power and mean power showed no significant change (within the 90% confidence intervals [CI] for absolute reliability) (Wolfe & Cumming, 2004) following fatiguing protocols. In this same study, time to peak power, time to peak force, FTCT, and eccentric duration were all outside of the 90% CI limits from baseline 72 hours post fatiguing protocol (Gathercole, Stellingwerff, et al., 2015b). As with reliability, the arbitrary nature of establishing smallest worthwhile change could be unhelpful in understanding the sensitivity of CMJ metrics. Measuring the change in response to training and games longitudinally and interpreting that relative to absolute reliability with CI established prior to the accumulation of load (Crowcroft et al., 2015; Thorpe et al., 2015) could be a more effective approach.

2.3.4. CMJ measurement characteristics

A meta-analysis by Claudino et.al. (Claudino et al., 2017) reviewed current trends in CMJ protocols and analysis with the objective of determining which methods and variables are best for applied use in monitoring neuromuscular status. In addition to examining measurement characteristics, the authors aimed to establish which variables showed adaptations to chronic interventions (i.e., > 3 weeks). Finally, they sought to establish which of the best score from a given trial (i.e., best jump from all those performed) or the average of the results across a series of trials (i.e., average of a given variable from all performed jumps) was best to detect neuromuscular change (Claudino et al., 2017). The review concluded that if a CMJ variable was to be used for the monitoring of neuromuscular status, three criteria should be met: i) the average of 3 or more trials should be used for each data point; ii) the absolute reliability should be high (i.e., CV <10%), and; iii) change should be interpreted by effect size in response to stimulus (ES >0.2 = moderate effect) (Claudino et al., 2017).

Several limitations in our current understanding of the utility of CMJ were acknowledged by the authors, the first of which was that of the 63 variables identified within the literature, 32 had only been researched in one intervention group, bringing into question the generalisability of these findings (Claudino et al., 2017). Additionally, 73% lacked sufficient sample size, thus requiring further investigation to establish efficacy or validity (Claudino et al., 2017). These results highlight the need for more research that explores the measurement characteristics of many variables (Claudino et al., 2017). Alongside these limitations, the adherence to arbitrary criteria (i.e., CV <10%, ES >0.2, and studies >3 weeks) may limit the generalisability of these and other findings. Indeed, relying on measurement characteristics taken from research alone is likely to be inadequate for the applied environment, requiring that practitioners employ their own ecologically valid approach to data collection and validation/utilisation (Coutts, 2017).

The proliferation of force plate systems in elite sporting environments (Bishop et al., 2021) has increased accessibility to data and, with it, multiple methods of measuring and delivering the data to practitioners (Eagles et al., 2015; Richter et al., 2014a; Sole et al., 2018). Indeed, three different methods for identifying phases in the CMJ have been found within recent literature (Eagles et al., 2015). One of the major discrepancies in variable calculation arises from the lack of agreement of the start of movement criteria (**Table 2.1**). Differences between definitions for start and end of each phase of the jump are also noted between each method, and investigation using a neutral dataset demonstrated that each of these methods resulted in significantly different outcomes for time-dependent variables (Eagles et al., 2015).

Table 2.1 - Definitions for analysis points in force-time curves according to Eagles et.al. (Eagles et al., 2015)

	Method 1	***Method 2***	***Method 3***
Start of Jump	5% Reduction in vertical ground reaction force from standing weight	Vertical ground reaction force exceeds a quiet standing value for the subject by 10N	Vertical ground reaction force exceeds a quiet standing value for the subject by 10N
Start Eccentric Phase		Calculated centre of mass starts descending	Calculated centre of mass starts descending
End Eccentric Phase	Minimum vertical ground reaction force recorded prior to the large Peak vertical ground reaction force	Calculated centre of mass reaches its lowest point	Calculated centre of mass has a velocity of 0 m/s
Begin Concentric Phase	End of Eccentric Phase	End of Eccentric Phase	Calculated centre of mass has a velocity of 0.1 m/s
End Concentric Phase	Leave time (vertical ground reaction force becomes <5N)	Leave time	Leave time

Data collection and treatment protocols vary between practitioners, presumably owing to the different intents or aims for the information gained from the CMJ, and where it fits into their conceptual framework for understanding athlete fitness and fatigue (Coutts et al., 2018; Jeffries et al., 2021). Some of the differences noted are protocols where only one jump is collected (Cormack, Newton, Mcguigan, et al., 2008a), data from a single jump amongst several is selected for use (Cormack, Newton, Mcguigan, et al., 2008b; Cormie et al., 2009a), or the average of multiple jumps is used (Gathercole, Sporer, et al., 2015b; Nibali et al., 2015), Additionally, how a trial(s) are selected for further use varies, with examples being the trial(s) with the greatest jump height (Laffaye et al., 2014; Nibali et al., 2015), and those jumps with the 'most consistent' results for a key metric (Gathercole, Sporer, et al., 2015b). As suggested by Claudino et.al., those groups aiming to longitudinally monitor athletes might be better to use the average of several trials (Claudino et al., 2017). However, Cormie et.al. used the average of 2 consecutive 'consistent' (i.e., peak power within 5% of the previous) trials to determine if significant change was noted following a 12-week resistance training protocol (Cormie et al., 2009b). The inconsistent rationales given for data collection and processing could lead to confusion for those practitioners looking to implement CMJ as part of their program.

This review highlights gaps in applied research focusing on the use of CMJ in athletes. Confounding factors such as differing methods for calculation of CMJ metrics, as well as data collection and processing, highlights the need for a ubiquitous process for establishing the measurement characteristics of each variable (Coutts, 2017), The sporadic nature of research examining certain CMJ metrics also indicates a need for examinations that examine a wider range of variables, thus contributing to a more robust literature in the area (Claudino et al., 2017), whilst also helping to highlight the potential utility of metrics that have not been used as frequently through previous studies(Gathercole, Sporer, et al., 2015a). Through this investigation of measurement characteristics, a further investigation of the moderating factors affecting CMJ performance, such as training and game load (Jeffries et al., 2021) can be examined, aiding in the development of parsimonious systems for real-time monitoring of neuromuscular status(Coutts, 2014).

2.4. Rugby Union

Rugby union is a sport physically characterised by intermittent, high-intensity activities including sprinting, tackling, scrummaging, and jumping, interspersed with lower-intensity activities such as jogging and walking (Duthie et al., 2003). The game demands a high level of physical conditioning to support these activities, with players covering an average distance of 6-8 km per game, of which a significant portion is at high physiological intensity (i.e., 75-95% of maximum heart rate) (Deutsch et al., 1998). These physical demands vary by position, with forwards participating in more static, strength-based activities and backs undertaking more dynamic, speed-based activities (Austin et al., 2011).

Empirical research utilizing global positioning system (GPS) technology has demonstrated that players cover, on average, between 6,400 and 7,000 meters per match, with backs typically accumulating greater distances than forwards due to the positional requirements of the game (Coughlan et al., 2011). While most of the match time is spent at lower intensities—characterized by standing, walking, or jogging—periods of high-intensity running, including sprinting at velocities exceeding 24 km/h, occur intermittently, particularly among backs (Coughlan et al., 2011; Reardon et al., 2017). In contrast, forwards engage in a greater volume of static and isometric exertions, such as scrummaging, rucking, and mauling, resulting in a higher cumulative body load over the course of a match (Reardon et al., 2017; Tierney et al., 2021).

Collisional events are a defining characteristic of professional rugby union, with research indicating that high-intensity collisions, exceeding 8 g-force, occur frequently throughout match play (Reardon et al., 2017; Tierney et al., 2021). Forwards, particularly tight five players, experience a greater number of impacts per match compared to backs, who engage in fewer but potentially more intense collisions due to their higher approach velocities prior to contact (Tierney et al., 2021). During worst-case scenario (WCS) bouts—prolonged passages of uninterrupted play—players cover distances of up to 318 meters at intensities reaching 117 meters per minute, which is significantly greater than the average match intensity (Reardon et al., 2017).

2.4.1. Training and monitoring

Training for rugby union must therefore be carefully structured to replicate the physical demands of match play, with a focus on developing cardiovascular endurance, muscular strength, power, speed, and agility. Periodised training programs that vary in intensity, volume, and type of training throughout the season are crucial to optimise performance and minimise the risk of injury (Gamble, 2004). High-intensity interval training (HIIT), plyometrics, and resistance training are integral components of a rugby training program, designed to prepare athletes for the specific physical demands they will face in games (Jones et al., 2016). The challenge for strength and conditioning professionals is to ensure that training is specific to the demands of the sport, including the replication of game intensity and scenarios within a controlled training environment.

Performance and medical teams utilise a variety of tools for monitoring athletes throughout their season, including wearable technology to quantify external load (Austin & Kelly, 2013; Cunniffe et al., 2009; Howe et al., 2020), strength and power tests to assess neuromuscular response (Cormack et al., 2013; Cormack, Newton, McGuigan, & Cormie, 2008; West et al., 2014), endocrine testing to assess physiological response (Cormack, Newton, McGuigan, & Cormie, 2008; McLean et al., 2010; McLellan et al., 2011), and psychological questionnaires to assess mental fatigue and perceived effort (Twist & Highton, 2013; West et al., 2014). By integrating data from these sources, teams can make informed decisions about training adjustments, recovery interventions, and readiness for gameplay, ensuring that players are prepared to perform at their peak while mitigating the risks associated with cumulative load (West et al., 2014). The strategic management of cumulative training and game load involves targeted training programs designed to progressively overload the player in a controlled manner, and individualised recovery protocols, including nutritional strategies, sleep hygiene, and active recovery methods, tailored to optimise recovery times (Nedelec et al., 2014).

2.4.2. Demands of different competitions

The physical demands of rugby union also vary significantly across different levels of competition and between hemispheres, influenced by factors such as the style of play, environmental conditions, and the rugby calendar. International rugby tends to be more intense and faster paced than provincial rugby, attributed to the higher skill levels and physical conditioning of the players (Quarrie et al., 2013). Furthermore, the physical and preparatory demands of elite rugby union exhibit notable differences between the Northern and Southern Hemispheres, shaped by a variety of factors including environmental conditions, styles of play, and historical traditions of the game (Austin et al., 2011; Quarrie & Hopkins, 2007; Roberts et al., 2008). Investigation highlighting the considerations of strength and conditioning practitioners shows that Southern Hemisphere teams often prioritise speed and endurance due to their generally more expansive style of play, which is facilitated by drier playing surfaces and a faster game tempo (Jones, Smith, et al., 2017). Indeed, observations of players in the

Super 14 Rugby competition through 2008 and 2009 showed that those players cover more distance at high intensity, underscoring the endurance and speed required in that competition (Austin et al., 2011). In contrast, practitioners in the Northern Hemisphere placed a greater emphasis on physical strength and power, a reflection of the typically heavier playing surfaces and the strategic preference for set-piece dominance and a more confrontational style of play (Jones, Smith, et al., 2017). This is empirically supported by research examining players involved in games in the English Premiership competition that show these players engage in more contact situations (i.e., scrummaging, rucking, mauling, and tackling) (Roberts et al., 2008). This difference in playing styles necessitates divergent approaches in physical preparation; while Southern Hemisphere teams may focus more on high-intensity interval training and agility drills to enhance player speed and endurance, Northern Hemisphere teams are likely to allocate more training time to strength and power development through resistance training (Jones, Smith, et al., 2017).

For performance staff working within these rugby environments, key considerations include tailoring conditioning programs to suit the prevalent style of play, environmental conditions, and player roles within the team. In the Southern Hemisphere a focus on recovery strategies that mitigate the effects of fatigue from high-intensity efforts is beneficial, while in the Northern Hemisphere protocols that address muscle damage and manage the longer-term impacts of physical collisions are of greater impact (Tavares et al., 2017). Therefore, the geographical dichotomy in rugby union extends beyond mere playing style; it influences the holistic approach to player development, conditioning, and recovery, necessitating a nuanced understanding of the game's demands by performance staff to optimise player performance and team success (Naughton et al., 2021; Young et al., 2012).

2.4.3. CMJ in Rugby Union

Despite the proven utility of the CMJ in monitoring neuromuscular performance, the evidence surrounding its use specifically for rugby union players at the elite level, particularly concerning its sensitivity to differentiating performance changes due to the cumulative demands of the sport, requires further exploration. While there is substantial literature attesting to the CMJ's reliability (Claudino et al., 2017; Cormack, Newton, Mcguigan, et al., 2008a; Heishman et al., 2018; Nibali et al., 2015), the specificity of its application to rugby union in this context warrants additional investigation. Existing literature examining changes in neuromuscular status using the CMJ use primarily sub-elite (i.e., academy level and age-grade athletes) in limited timeframes (i.e., through a pre-season or short-period intervention (Kennedy & Drake, 2018; Roe et al., 2017; Roe, Till, et al., 2016; Roe, Darrall-Jones, et al., 2016). Future research should aim to refine the understanding of how CMJ metrics correlate with rugby-specific training loads and the variation in training throughout an entire season, aiming to elucidate the sensitivity and specific response to cumulative training and game loads, ensuring its effectiveness as a monitoring tool is maximised for this population.

2.5. Conclusion and future research directions

This literature review has highlighted the critical role of neuromuscular performance in elite sports, with a specific focus on rugby union. It underscores the importance of accurate and reliable monitoring tools to assess neuromuscular function in professional athletes. The review also identifies limitations of existing methods, noting the challenges associated with complex and time-consuming procedures, like electromyography, and proposes the CMJ as a practical and ecologically valid alternative.

Despite the advancements in neuromuscular monitoring, several gaps remain in our understanding of how CMJ variables can be optimised for use in longitudinal monitoring of elite athletes, specifically the reliability, sensitivity, and co-variance of a wide range of the variables available from contemporary force plate software systems, and investigations in elite-level athletes, particularly in rugby union. Future research should focus on better understanding the sensitivity of CMJ metrics to detect subtle changes in neuromuscular function across different training and competition phases. Additionally, robust research is needed to examine the interrelationships among CMJ variables, employing statistical methods to reduce data complexity while preserving essential information. Such research could provide a clearer understanding of which variables are most indicative of neuromuscular fatigue and recovery, thus enhancing their practical application in elite sports settings.

Furthermore, future studies should investigate the application of CMJ monitoring within diverse athletic populations and sports contexts. Although this investigation focused on rugby union, multi-centre studies that include other high-performance environments could compare results for different athletes and training plans. This approach would not only validate the generalisability of the findings but also refine sport-specific monitoring protocols. Research should also consider integrating CMJ data with other monitoring tools, such as external (e.g., running volumes, resistance training volumes) and internal (e.g., subjective wellness measures, session rate of perceived exertion) loads, to develop a more holistic understanding of athlete status and inform more effective training prescription and management strategies.

Chapter 3

Methods Section:

Using measurement characteristics to select CMJ kinetic variables for use in longitudinal monitoring: A technical report

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Howarth, D. J., McLean, B. D., Cohen, D. D., & Coutts, A. J. Using measurement characteristics to select CMJ kinetic variables for use in longitudinal monitoring: A technical report.

3.1. Preface

In Chapter 2, we established that there is a lack of coherent frameworks for dealing with the large amount of data created by measuring CMJ on force platforms. This chapter proposes a framework for an agnostic approach to understanding the measurement characteristics of CMJ variables, and summarising the statistical techniques used in Chapter 4, Chapter 5, and Chapter 6. Through this we seek to explain the rationale behind these techniques and how they may be applied to future research and practical application.

3.2. Abstract

Athlete performance optimisation relies on understanding training inputs and their effects on physiological, psychological, and biomechanical factors. We propose a framework focussing on essential measurement characteristics, namely reliability, sensitivity, and covariance, in a representative environment to refine variable selection methodologies. This framework integrates statistical methodologies to support the objective selection of CMJ variables, minimising biases, and enhancing data interpretability. Our systematic and agnostic approach to CMJ variable selection includes establishing noise (absolute test/re-test reliability and week-to-week variation), determining the signal (longitudinal SNR), reducing the noise (PCA for co-variance analysis), and selecting variables (based on highest SNR). Applied to a case study involving professional rugby union players, this framework effectively identifies sensitive CMJ variables indicative of neuromuscular performance. Our findings support the development of parsimonious systems for athlete monitoring, balancing the need for detailed analysis with practical application in high-performance sports and enhancing practitioners' ability to interpret CMJ data. By refining variable selection processes, this framework contributes to the broader field of sports science, providing a replicable model for future studies and practical applications.

3.3. Introduction

In order to optimise athletes' preparation for competition, practitioners seek to quantify training input (i.e., internal and external training load) and training effect (i.e., physiological, psychological, biomechanical) to understand the ‘performance readiness’ of individuals and teams (Jeffries et al., 2021). Ultimately, these measures aim to inform practitioners about the improvement, maintenance, or decrement of sport performance outcomes (Jeffries et al., 2021). A range of techniques and technologies are commonly used to measure training load and athlete responses, in order to guide training prescription (Coutts et al., 2018). All of these tools produce distinct data sets which require systems to manage collection, collation, analysis, and interpretation. The quantification of load and response leads to large amounts of data in contemporary professional sports programs. Consequently, systems that embrace the concept of parsimony (i.e., not using more resources than necessary) (Coutts, 2014) while respecting that results are individualised and nuanced (Cohen, 2020), are essential in a dynamic environment focused on sport performance outcomes, and accurate training prescription to develop those outcomes.

In line with these concepts, the CMJ is commonly employed to assess both the chronic effects of neuromuscular training adaptations —such as those resulting from power, speed, and strength training (Cormie et al., 2009b; Cronin & Hansen, 2005; Hennessy & Kilty, 2001)— as well as the acute impacts of gameplay and fatiguing exercises (Cormack, Newton, & McGuigan, 2008; Gathercole, Stellingwerff, et al., 2015b; Gathercole, Sporer, et al., 2015a). This dynamic assessment utilises force plates to capture data, which is then analysed using various software to generate a spectrum of kinetic outputs including force, time, power, velocity, and acceleration (Claudino et al., 2017; Cohen, 2020; Cohen et al., 2020; Cormie et al., 2009b; Cormie et al., 2010; Eagles et al., 2015; Gathercole, Sporer, et al., 2015a; Merrigan et al., 2022). While the CMJ can provide valuable insights to practitioners, the utility of this data is often compromised by several challenges. Indeed, before even considering changing training interventions, it is challenging to interpret CMJ outputs due to the vast range of available variables (i.e. up to150 (Bishop et al., 2021; Merrigan et al., 2022)) ,along with analysis software using inconsistent calculation (i.e. the same variable calculated in multiple ways), and varied nomenclature (i.e. different variable names for same calculation) (Eagles et al., 2015; Merrigan et al., 2022). Additionally, published literature aiming to better understand CMJ variables has often used arbitrary selection criteria to include or exclude variables for analysis, which further complicates the research findings and subsequent interpretation of CMJ data (Claudino et al., 2017). These factors collectively contribute to a confusing landscape of results, which can hinder the ability of practitioners to effectively interpret and apply results from CMJ data in practical settings.

Recognising the challenges posed by confounding data processing and the complexity of managing large datasets, alternative approaches to analysing CMJ data need to be developed to better support practitioner decision-making. This may be achieved by firstly focusing on essential measurement characteristics—namely reliability, sensitivity, and covariance—in a representative environment (Chapter 4, Chapter 5, and Chapter 6). This combined approach improves upon the methodological rigor of previously published processes (e.g. arbitrary cut-offs or subjective decisions to eliminate variables), ensuring that the variables selected are ecologically valid (as tested in a representative environment) and such a protocol-based approach may be applied across different cohorts and monitoring systems (i.e., broader than just CMJ). Furthermore, developing a rigorous statistical methodology will help support objective and agnostic selection of CMJ variables that are most indicative of the neuromuscular performance of the specific cohort, while also removing any biases or preconceptions about variables and their utility.

This technical report aims to outline a decision-making framework for practitioners to select a manageable number of CMJ variables, whilst retaining the most important information to inform athlete monitoring systems. We propose a replicable model for future research and practical applications in sports science, which prioritises parsimonious systems, without compromising the depth and integrity of the analysis.

3.4. Statistical considerations

One major challenge facing practitioners and researchers dealing with CMJ data, is that a range of statistical concepts and techniques are often mis-used, mis-represented, or poorly reported upon within the sports science literature. Therefore, to support methodology in subsequent sections, this section outlines commonly used, and often mis-represented, statistical techniques commonly applied to CMJ, and other athlete monitoring data.

3.4.1. Reliability

In sports medicine research, reliability refers to the consistency of a measurement or test over repeated trials with the same individuals, indicating the precision of single assessments and their efficacy in tracking changes over time (Hopkins, 2000). Changes between trials generally arise from systematic bias, such as learning or fatigue effects, and random error stemming from methodological and biological variations (Atkinson & Nevill, 1998). It is important to accurately quantify both systematic and random error, as this variation helps practitioners understand which changes noted during routine testing are indeed 'real differences', rather than relying solely on the statistical significance of reliability indicators (Atkinson & Nevill, 1998; Hopkins, 2000).

3.4.1.1. Relative reliability

Relative reliability examines the consistency of rank-order of subjects within a group between tests and is commonly assessed using correlation coefficients and regression analyses, like the intra-class correlation coefficient (Atkinson & Nevill, 1998). The validity of these methods is heavily dependent on the range of measured values and is highly specific to the sample tested (Atkinson & Nevill, 1998). Researchers must therefore exercise caution when interpreting high correlations as 'acceptable reliability', extrapolating test-retest results to new samples, and comparing correlations across different studies. In practical terms for the CMJ, this investigation uncovers whether, under normal conditions, the athletes who exhibit higher (or lower) scores in CMJ variables reliably do so day-on-day. This can be an important understanding for practitioners looking at the level of familiarisation needed for athletes in their cohort (Nibali et al., 2015).

3.4.1.2. Absolute reliability

For absolute reliability, measures of within-subject variation such as the typical error (Hopkins, 2000) and limits of agreement (Atkinson & Nevill, 1998) are utilised. These metrics are particularly useful for assessing and comparing the reliability of different measurement tools across studies. The typical error is a direct measure of within-subject variation and is often expressed as a percentage of the mean, or coefficient of variation (CV%), but can also be presented in the relevant units of measure (Hopkins, 2000). It is important to consider in test-retest studies to understand the magnitude of true changes (relative to the inherent error of the measurement) and estimating statistical power in repeated-measures experiments (Atkinson & Nevill, 1998; Hopkins, 2000).

3.4.1.3. Inter-day reliability

Inter-day reliability is calculated using test-retest data on two separate yet similar days (Atkinson & Nevill, 1998). For the current research, we have chosen the intra-class correlation coefficient (ICC) to measure the relative reliability (i.e., the consistency of cohort rank-order) (Atkinson & Nevill, 1998). As a measure of absolute reliability (i.e., the normal methodological and biological variation), the typical error, presented as a CV% (Atkinson & Nevill, 1998; Hopkins, 2000) are used. Both measures have been proposed as criteria for evaluating 'usefulness' of CMJ variables (Claudino et al., 2017; Cormack, Newton, Mcguigan, et al., 2008a), though for the context of monitoring CMJ variable change longitudinally, we focus on the CV% (Hopkins, 2000). Knowing the CV% for a particular variable enables the practitioner to evaluate observed changes over time relative to the expected methodological and biological variation, or "noise" (Hopkins, 2000).

3.4.2. Sensitivity

Sensitivity measures the responsiveness of an outcome measure to given stimuli and can be either discrete or cumulative (Currell & Jeukendrup, 2008). To give context to the magnitude of changes, sensitivity is often represented by a signal-to-noise ratio (SNR) that compares the magnitude of change observed in an outcome measure ("signal") to a pre-determined amount of expected variability ("noise") (Currell & Jeukendrup, 2008). An SNR > 1.0 indicates that the changes in the outcome measure (signal) are greater than the inherent variability (noise) and may lead to the conclusion that the variable is 'sensitive' to the stimuli applied (Crowcroft et al., 2017). However, using a discrete threshold of 1.0 is binary in nature and does not allow for nuanced interpretation of outcome measure sensitivity. Therefore, this sensitivity measure should be considered as a spectrum, whereby calculating this SNR allows for interpretation about the likely sensitivity of a given measure and allows for comparison of sensitivity across different measures (e.g. comparing different CMJ variables). In the context of team-sport athlete monitoring, a longitudinal approach to calculating SNR has been employed, which measures 'signal' as within-subject variation across the whole training and competition period and compares this to baseline inter-day reliability (Crowcroft et al., 2017; Ryan et al., 2019b)). This approach allows the use of the same metric (i.e., typical error as a CV%) to be used for both measurements, quantifying the ratio of change in response to training and competition longitudinally, to change arising from normal and methodological variation (Mercer et al., 2021; Ryan et al., 2019b). In Chapter 5, we proposed that the SNR required more careful consideration, as both measures of signal and noise also involved elements of error as they are group-level assessments. This ratio can be better interpreted by considering the 95% confidence intervals (CIs) for each . Non-overlap of 95% CIs indicates a greater likelihood that a variable is sensitive for each individual (i.e., significant difference between both sides of the ratio) (Wolfe & Cumming, 2004). Such evaluation is more helpful for interpreting SNRs than relying on heuristics for evaluation (e.g., classification of "good/adequate/excellent") , This technique has some important limitations to consider, particularly when using small sample sizes (Wolfe & Cumming, 2004). Small samples create larger intervals because of the lower statistical power (Wolfe & Cumming, 2004), lowering the likelihood of finding variables with non-overlap of CIs.

3.4.3. Co-variance

Co-variance is a measurement characteristic that describes the correlation between variables within a dataset and the overlap between them in terms of explaining the overall data (dimensionality). When multiple variables are collected from a single source of data, there is a chance that the variables reported are measuring the same construct (Matsunaga, 2010). This can create redundancy in testing and variables from the same test (e.g. CMJ) and such redundancy is important to understand when seeking to develop parsimonious monitoring systems. One analysis that identifies the emergent structures from multiple variable results is principal component analysis (PCA) (Matsunaga, 2010; Ryan et al., 2021). PCA uses correlation matrices to highlight where variables co-vary, organising 'components' of highly correlated variables (Matsunaga, 2010; Merrigan, Rentz, et al., 2021). The concept of variable redundancy is not unique to CMJ kinetic information, with prior research examining potential redundancy of GPS metrics (Ryan et al., 2021; Weaving et al., 2019; Weaving et al., 2018) using PCA. Data reduction using components includes creating composite scores from multiple variables change data (Matsunaga, 2010) or selecting one representative variable for each component (Ryan et al., 2021).

3.5. Agnostic approaches to inform variable selection

This section outlines an agnostic variable selection process, which may be applied in many different scenarios, but is presented here through the lens of accumulating the results from three studies (Chapter 4, Chapter 5, and Chapter 6) that examine the measurement characteristics of CMJ variables from one group of professional rugby union players . Prior to embarking on this process, an extensive review of the literature was performed, followed by workshopping the process with a group of experts (the research team). The following framework can then be divided into these 4 procedures (outlined in **Figure 3.1**):

1. Establish the noise
2. Determine the signal
3. Reduce the noise

4. Select variables

This process functions to reduce the number of variables for CMJ monitoring, which provides a systematic and agnostic approach to CMJ variable selection when many variables are available for use. These individual steps are outlined in more detail in the following sections.

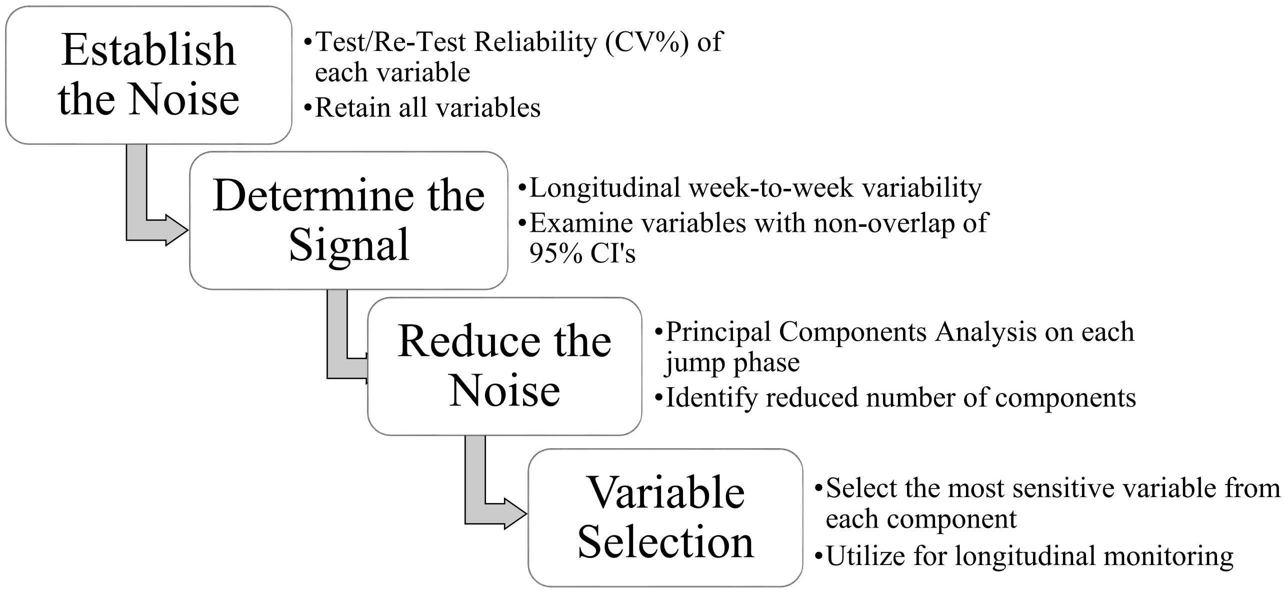

Figure 3.1 - Representation of the systematic and agnostic approach to CMJ variable selection for longitudinal monitoring.

3.5.1. Establishing the noise

Absolute test/re-test reliability and week-to-week variation throughout the season are assessed by calculating the absolute variability (CV%) for both (Hopkins, 2000). Several data treatment methods (i.e., average of multiple jumps [$Mean_3$] and the 'best' jumps as determined by jump-height [$Best_{JH}$] and flight time/contraction time ratio [$Best_{FTCT}$]) are examined to see if one provided more reliable or sensitive metric results (Claudino et al., 2017). The within-subject variation is then measured by the typical error of measurement expressed as a CV% for both test-retest reliability ("noise") and longitudinally ("signal"). The ratio of these 2 CV% measures are then used to construct the SNR; the signal measure as the antecedent (numerator) and the noise measure as the consequent (denominator) (Crowcroft et al., 2017; Ryan et al., 2019b). To qualify sensitivity, an examination of the 95% CIs for both signal and noise gave important information on the likelihood that an individual within this group would provide sensitive data (Sole et al., 2018; Wolfe & Cumming, 2004). Variables displaying non-overlap of 95% CIs can be considered most sensitive and most likely useful in evaluating individual change throughout a season .

3.5.2. Finding the signal

Multiple methods can be used to determine the sensitivity of a given variable or test, and in this instance a longitudinal approach to establishing the SNR by establishing a ratio of the CVs for signal (week-to-week typical error) and noise (inter-day absolute reliability) is used. Examination of sensitivity results will show the most appropriate data treatment method for establishing sensitivity. With measures of absolute reliability and sensitivity established, a method of identifying redundancies within the dataset is necessary to a manageable number the variables used for further study, which can be established through the understanding of co-variance within the variables available (Ryan et al., 2021).

3.5.3. Reducing the noise

To assist in the reduction of the variable list for ongoing monitoring, one of the main sources of confusion when using any technology where large numbers of variables (dimensions of data) are calculated, we propose exploring them for co-variance. In this case, principal components analysis (PCA) can be used, which is a data exploration procedure that identifies the principal components—directions of maximum variance in the data—using correlation matrices (Matsunaga, 2010). This allows the dataset to be reduced to fewer variables, while still preserving all the information in it, along with its essential patterns and relationships (Abdi & Williams, 2010). Four PCAs are conducted on the data from a single day, one for each variable grouping. All variables examined in the sensitivity investigation are included in the PCA, with analysis 'informed' by grouping variables by the phase of the CMJ from which they are calculated – eccentric, concentric, and landing. Where a variable is not calculated in a discrete phase, it will be categorised as a 'composite' variable. These same procedures are then repeated for a second day of data to assess the consistency of the results.

Several different methods of data reduction have been suggested for use post-PCA (Matsunaga, 2010). For example, the creation of a composite variables that average the change across those within a component (James et al., 2021), or picking the variable with the single highest loading to the overall component structure (Matsunaga, 2010). However, with the collective understanding of reliability and sensitivity, the preferred method for this process is to pick the variable within each component that is most likely to demonstrate change throughout the season. Therefore, the variable with the highest SNR from each component will be selected to ensure that each emergent structure is represented by a variable that can detect change longitudinally. By selecting one variable, all data is retained rather than transformed into a composite score, and where response is noted to training prescription in that measure of neuromuscular status, the other variables can still be examined to better understand the individual's mechanical changes (Sole et al., 2018).

3.6. Discussion

This technical report outlines a process to support the selection of CMJ variables using agnostic statistical approaches. The methods presented here focus on analysing measurement characteristics with statistical rigor. This process is integral to creating evidence-based frameworks for high-performance sport. Understanding variable calculation (i.e., temporal and kinetic measurements) and the meaningfulness of these variables is also essential for interpreting results and applying them in specific contexts.

In recent years, CMJ monitoring has become increasingly popular within high-performance sport science programs (Bishop et al., 2023; Bishop et al., 2021; Cohen, 2020). With this popularity, reviews and best-practice frameworks have been collated to share what the 'weight of evidence' would suggest with regard to selecting CMJ variables for athlete monitoring (Bishop et al., 2023; Bishop et al., 2021). However, many of the studies referenced within these frameworks implore practitioners to study and understand the tendencies of their own cohorts (Gathercole, Stellingwerff, et al., 2015b; Gathercole, Sporer, et al., 2015a). Indeed, studies examining measurement characteristics within different cohorts have noted variations in reliability depending on athlete chronological and training age (Nibali et al., 2015), and varying levels of sensitivity to stimuli such as resistance training (Cormie et al., 2009b; Cormie et al., 2010; Marshall et al., 2021), running loads (Twist & Highton, 2013), and physical contact (Roe et al., 2017; Roe, Till, et al., 2016; Tavares et al., 2017). This combined evidence would suggest that a systematic process that examines the direct cohort that the practitioner is working with is the best approach to 'selecting metrics that matter' (Bishop et al., 2023).

With combined knowledge of measurement characteristics, an examination of the moderating factors affecting CMJ variables (i.e., training effects) can be undertaken. Research examining training effects on neuromuscular status as measured by CMJ variables should focus on the acute and chronic responses (Jeffries et al., 2021). This can be interpreted through a conceptual framework of training load monitoring (Jeffries et al., 2021) which includes the identification of measures of training load, training effects as quantified by neuromuscular status, along with any other individual and contextual factors.

Chapter 4

Study 1:

Establishing the noise: Inter-day ecological reliability of countermovement jump variables in professional rugby union players

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Howarth, D. J., Cohen, D. D., McLean, B. D., & Coutts, A. J. (2022). Establishing the noise: Inter-day ecological reliability of countermovement jump variables in professional rugby union players. *The Journal of Strength & Conditioning Research*, *36*(11), 3159-3166.

4.1. Preface

Chapter 3 details an agnostic framework for establishing the important measurement characteristics of CMJ variables. This chapter explores the first of these: Reliability. Through this study we establish both the relative reliability and the absolute reliability of CMJ variables, which informs practitioners of the normal methodological and biological variation expected when monitoring athletes neuromuscular status.

4.2. Abstract

The purpose of this study was to examine the inter-day 'ecological' reliability of a wide range of ground reaction force derived countermovement jump (CMJ) variables. Thirty-six male, professional rugby union players performed 3 CMJ's on 4 separate days over an 8-day period during the first week of pre-season. We calculated reliability for 86 CMJ variables across 5 inter-day combinations using 2 criteria: mean output across 3 jump trials ($Mean_3$) and single output from the highest jump ($Best_{JH}$). Inter-day CV of the 86 variables in each CMJ phase, for $Mean_3$ and $Best_{JH}$ respectively, ranged between: Concentric =2-11% and 2-13%; Eccentric =1-45% and 1-107%; Landing =4-32% and 6-45%. $Mean_3$ inter-day CV was lower in all 86 variables across every inter-day combination, compared with $Best_{JH}$. CVs were lower in our cohort than previous studies, particularly for eccentric phase variables. There was no meaningful difference between inter-day conditions, suggesting any 2-day combination conducted within the first 8 days of preseason, represents a measure of 'noise'. We did not apply arbitrary reliability 'cut-offs' used in previous work (e.g., CV<10%), therefore our analysis provides reference reliability for a wide range of CMJ variables. However, we recommend that practitioners assess reliability in their athletes, as it is likely to be environment, protocol and cohort specific.

4.3. Introduction

Countermovement jumps (CMJ's) are commonly used to assess athlete's lower body physical capacity, evaluate changes in neuromuscular status and subsequently inform training prescription (McMaster et al., 2014). Early work proposed CMJ height as a valid measure to assess the effectiveness of strength and power training protocols (Claudino et al., 2017), due to its relationship with performance in dynamic tasks such as sprint acceleration (Cronin & Hansen, 2005). However, meaningful changes in CMJ kinetic variables derived from ground reaction forces measured on force platforms are observed in response to competition or chronic training, while jump height has remained stable (Gathercole, Stellingwerff, et al., 2015b; Kijowksi et al., 2015). This suggests that kinetic variables (Cormie et al., 2009b) may better inform practitioners about athlete status and individual responses to competition and training stressors (Cormack, Newton, Mcguigan, et al., 2008a; Gathercole, Stellingwerff, et al., 2015b).

Regular monitoring of kinetic variables is now common in high-performance sports programs as they have increased portability of force platform systems and the automation of ground reaction force analysis (Cohen, 2020). However, for data from tests used in athlete monitoring to meaningfully inform decision-making, practitioners need to distinguish training-related changes (i.e. 'signal') from methodological and biological variability (i.e. 'noise') (Claudino et al., 2017). Therefore, the relationship between the signal and the noise of CMJ variables, within relevant training and competition environments, is needed to help practitioners interpret individual athlete responses (Hopkins et al., 2001; Thorpe et al., 2017).

A wide range of CMJ kinetic variables have been reported in athlete monitoring studies (Cormack, Newton, Mcguigan, et al., 2008a; Gathercole, Sporer, et al., 2015a; Heishman et al., 2018), with a recent meta-analysis identifying 63 unique variables in the literature (Claudino et al., 2017). However, the same meta-analysis (Claudino et al., 2017) highlighted that 46 of these variables have been examined only once or twice, leading the authors to conclude that further investigation is required. In addition to further examination of the 63 CMJ variables identified by Claudino et al (Claudino et al., 2017), there are other potentially meaningful variables that can be derived from the force-time, velocity-time, power-time and displacement-time data available. Despite the widespread use of the CMJ in monitoring of athletes, few reliability studies have been conducted in highly trained populations (i.e., professional athletes with training age ~ 5 years) (Cormack, Newton, Mcguigan, et al., 2008a; Ryan et al., 2019b; Thorpe et al., 2015). Well controlled reliability studies typically collect data over 2-3 days of testing without any substantial training between each testing day, experimental conditions achievable with the university students or recreational athletes that are typically used in laboratory-based studies. These conditions are, however, generally not feasible with professional athletes, as they would require disruption of normal training routines. This issue was addressed in professional soccer by evaluating players over 2 consecutive days, with the first a day prior to the start of pre-season (Thorpe, 2018). As this approach may not be practical in all professional environments, further exploration of 'ecologically valid' approaches to establish noise are warranted. These should aim to assess athletes within the most stable periods of training (e.g., minimising the influence of acute stressors such as competition or accumulated fatigue). Therefore, the primary purpose of this investigation was to examine the inter-day reliability of a wide range of CMJ kinetic variables, using 'ecologically valid' and widely applicable assessment protocols, in professional rugby union players.

4.4. Methods

4.4.1. Experimental approach to the problem

To evaluate the 'noise' of CMJ kinetic variables using ecologically valid protocols, a group of professional rugby players were assessed on 4 training days within an 8-day period. Data was collected during the first week of the pre-season immediately following a 5-week off-season break (for testing and training schedules see Table 1). Each player was previously familiarised with the testing protocol (i.e., single CMJ with hands on hips) as 'returning' players (i.e., played with the club previously) had participated in CMJ testing twice a week for the entire previous season (n=31). All 'new' players (i.e., had not played with the club previously) completed similar CMJ testing in prior seasons at previous clubs, and also performed 2 familiarisation sessions of the protocol in the week prior to pre-season commencing (n=5).

Table 4.1- Testing and training schedule over the duration of the study

	$Monday_1$	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	$Monday_2$
09:00 - 09:45	CMJ [1,2,4,5] Monitoring	CMJ [1,3,5] Monitoring	NO TRAINING	CMJ [2,3,5] Monitoring	Monitoring	NO TRAINING	NO TRAINING	CMJ [4] Monitoring
09:45 - 12:30	Resistance training (60 min) Low intensity rugby skills (60 min)	Resistance training (60 min) Low intensity rugby skills (60 min)		Resistance training (60 min) Low intensity rugby skills (60 min)	Resistance training (60 min) Low intensity rugby skills (60 min)			Resistance training (60 min) Low intensity rugby skills (60 min)
14:30 - 14:45	Mobility	Mobility		Mobility	Mobility			Mobility
14:50 - 16:00	Cross training (60 min)	Running (45 min)		Cross training (45 min)	Running and high intensity rugby skills (60 min)			Running and high intensity rugby skills (45 min)

Abbreviations: CMJ = countermovement jump; Cross training = combination of aerobic and anaerobic conditioning, including high intensity interval training on cycling and rowing ergometers, high repetition dumbbell and kettlebell work, rope and medicine ball training; Monitoring = musculoskeletal assessments (closed-chain ankle dorsi-flexion, sit and reach, adductor strength) and wellness questionnaire; 1= CMJ data used in *Condition 1* ($Monday_1$-Tuesday); 2 = CMJ data used in *Condition 2* ($Monday_1$-Thursday); 3 = CMJ data used in *Condition 3* (Tuesday-Thursday); 4 = CMJ data used in *Condition 4* ($Monday_1$-$Monday_2$); 5 = CMJ data used in *Condition 5* ($Monday_1$-Tuesday-Thursday)

4.4.2. Subjects

Forty-three rugby union players who compete in the Pro 14 and European Challenge Cup competitions were invited to participate in this study. From this initial group, 3 players were not present during the testing period due to National Team commitments and 4 were omitted from regular CMJ testing by team staff due to injury. Therefore, the final cohort consisted of 36 male, professional rugby union players (mean ± SD; age 24 ± 5 y, height 184.8 ± 8.1 cm, body mass 103.1 ± 11.9 kg, Academy and Professional career = 6 ± 3 y). All players provided written informed consent to participate in this study, which was approved by the Human Research Ethics Committee at the University of Technology Sydney (ETH19-3614).

4.4.3. Procedures

During the testing week players were encouraged to maintain their habitual daily routines and completed testing in the same individual 15-minute period, with all tests taking place between 09:00 and 09:45. Prior to testing, the following standardised warm-up was completed twice: (i) self-selected soft tissue and mobility work; (ii) 5 band resisted overhead squats; (iii) 5 band resisted Romanian deadlifts; (iv) 3 band resisted broad jumps; (v) 10 pogo jumps, and (vi) 10 m of A-Skips. A 25 mm power band (BLK Box, Belfast, Northern Ireland) was used as resistance for the aforementioned 'band resistance' exercises. Each player performed CMJ testing within 2-3 minutes of completing the warm-up.

CMJ's were performed on a dual force plate system (NMP ForceDecks FD-4000–Vald Performance, Brisbane, Australia) connected to a Dell Latitude E5440 laptop computer. A known weight (20 kg) was used to check the accuracy of force measurement every testing day before the testing period. The acceptable error upon weighing the plate was ± 0.1 kg. To begin the test, players stood with one limb on each platform with hands on hips and remained still for ~5 s in order to obtain a stable body-mass, which was subsequently checked against calibrated scale (Seca, Model 875, Germany) measurement. Where any discrepancy was found between force plate and scale measures for player or calibration weight, the force plates were re-zeroed, and weight was measured again on both pieces of equipment to determine the source of the discrepancy. Before jumping, a maximal performance focus was established with each player through verbal cueing to "jump as high as you can and land on the plates." An external attentional focus was employed as previous literature supports this methodology for maximising performance of athletic tasks (Wulf, 2013). This verbal cue was employed throughout all testing with staff consciously avoiding additional or varied 'coaching' cues regarding jump strategy. Players performed 3 maximal CMJ's separated by 10-15 s, when they re-positioned their feet and prepared for another maximal effort. Testing was conducted in groups to encourage players to compete with each other during the test. After completing 3 repetitions, analysis of the CMJ force-time curves was completed using ForceDecks software (v2.0.7418, Vald Performance, Brisbane, Australia) via methods described elsewhere(Eagles et al., 2015; Linthorne, 2001), and depicted **Figure 4.1** (Cohen et al., 2020). Players received immediate visual feedback of individual jump height (derived from flight time) through a digital display (ForceDecks Leaderboard v.2.0.7418, Vald Performance, Brisbane, Australia) in the testing area.

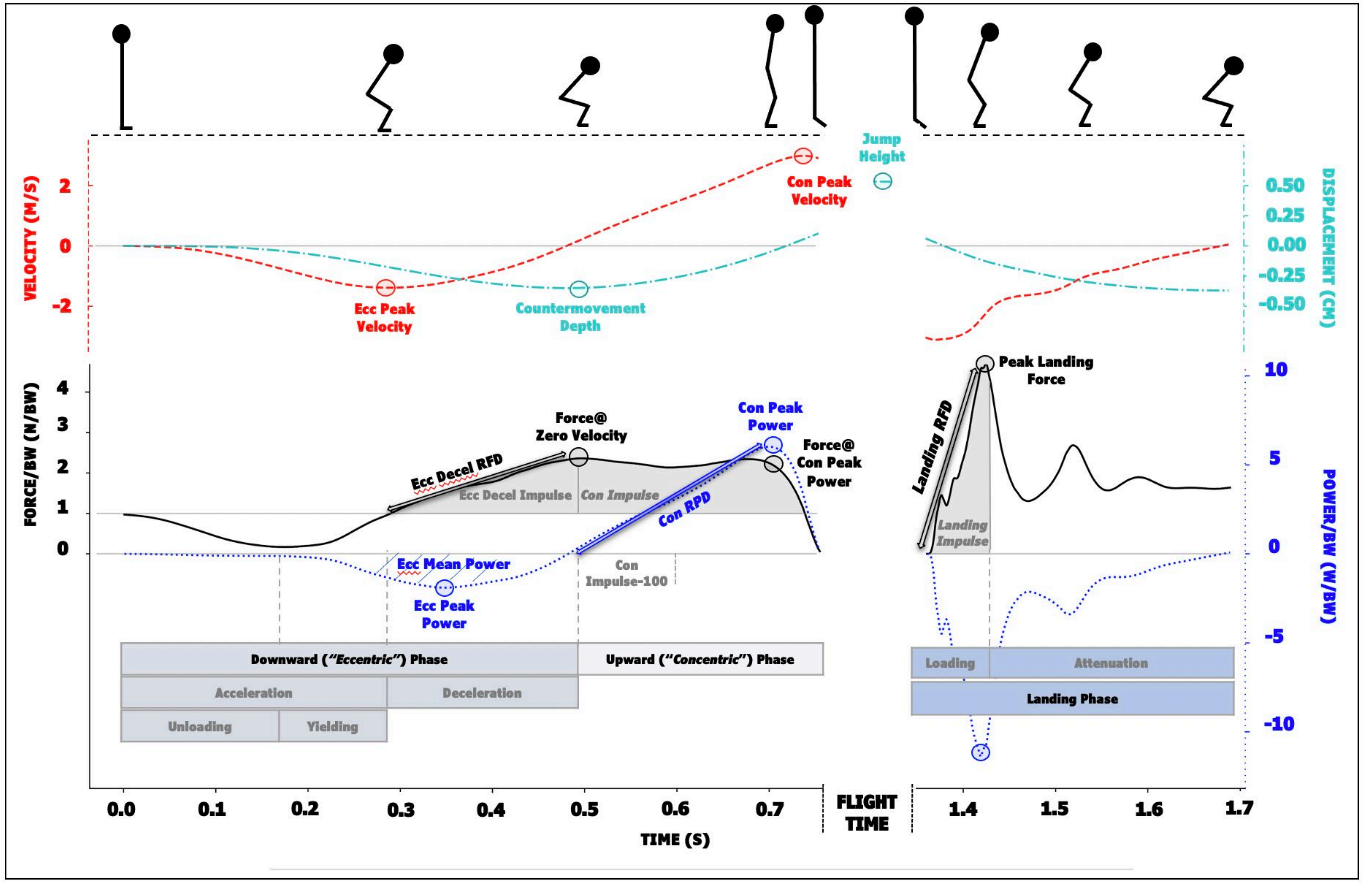

Figure 4.1 - Sample countermovement jump force, power, velocity and centre of mass displacement curves for CMJ.

Phases, sub-phases and selected variables shown as reference points for metrics evaluated. Ecc = eccentric; Con = concentric; Decel = deceleration; RFD = rate of force development; RPD = rate of power development Adapted from Cohen et.al. (Cohen et al., 2020) and reproduced with permission from the authors and publishers.

Every CMJ was visually monitored by an experienced staff member and any jumps deviating from standard protocol (e.g., jumpers attempted to 'tuck' their legs during the flight phase, double jump/pre-jump, did not land on the force plates) were excluded, and another jump performed to ensure 3 acceptable trials.

4.4.4. Statistical analyses

Before statistical analyses were undertaken, 86 bilateral variables (i.e., derived from total vertical ground reaction force) were selected from the eccentric, concentric, flight and landing phases of the jumps. Eighteen bilateral variables calculated by the software were not selected, as they are meta-data used in investigation or calculation of the included variables. Inter-day reliability was evaluated using 2 criteria: 1) Mean output across 3 jump trials ($Mean_3$)(Claudino et al., 2017), and; 2) Single output for each variable from the trial with the highest jump calculated by flight time ($Best_{JH}$) (Cormie et al., 2009b). These analyses were applied across 5 different combinations as shown in **Table 4.1**.

Statistical analyses were carried out in R statistical software (R Development Core Team, 2010) and the code used for analysis is available in the supplementary material. We chose 24 variables for display in **Table 4.2**, **Table 4.4**, **Table 4.4** and **Table 4.5**, that have been examined in prior research. Reliability was calculated according to procedures suggested by previous research into the reliability of dynamic athletic tests (Hopkins et al., 2001). Relative reliability, indicating the degree to which individuals maintain their position in a sample, was measured by the intra-class correlation coefficient (ICC; two-way, mixed, absolute). Absolute reliability, referring to the degree which repeated measures vary for individuals, was measured by the CV.

4.5. Results

In each jump phase, ranges for inter-day CV of the 86 variables were: concentric: 1.7 - 11.0% ($Mean_3$) and 1.9% - 13.4% for ($Best_{JH}$), eccentric: 0.7 - 44.6% ($Mean_3$) 0.8 - 107.3% for ($Best_{JH}$), landing: 4.1 - 32.0% ($Mean_3$) 6.3 - 45.0% for ($Best_{JH}$). Inter-day CV for all variables was less than or equal to $Best_{JH}$ when calculated by the $Mean_3$, when comparing by condition (i.e., Conditions 1-5). $Mean_3$ inter-day CV was lower in all 86 variables across every inter-day combination (i.e., Conditions 1-5), compared with $Best_{JH}$ (see Tables 4 and 5). As concentric rate of force development (RFD) may be positive or negative in the CMJ(Atkinson & Nevill, 1998), absolute reliability could not be calculated.

The ICC for 81/86 variables was > 0.7 for both $Mean_3$ and $Best_{JH}$ in ≥ 3/5 conditions. Variables with ICC < 0.7 in ≥ 3/5 conditions included: concentric time to peak force, velocity at peak power, concentric RFD, concentric RFD at 50ms and concentric $RFD{\cdot}BM^{-1}$. Compared to all other conditions, Condition 5 (i.e., $Monday_1$–Tuesday–Thursday) demonstrated the highest ICCs in both $Mean_3$ and $Best_{JH}$ in 58/86 variables.

Full results for reliability analyses (mean, standard deviation, ICC and CV) are available in the Appendices.

Table 4.2 - Inter-day absolute reliability (CV) and 95% confidence intervals of countermovement jump variables using $Mean_3$

Variable	Mean (±SD)	Condition 1 Mon-Tue		Condition 2 Mon-Thu		Condition 3 Tue-Thu		Condition 4 Mon-Mon		Condition 5 Mon-Tue-Thu	
Body Weight (kg)	**102.8 (12)**	0.7	*(0.7 - 0.9)*	0.9	*(0.8 - 1.1)*	0.9	*(0.8 - 1.1)*	1.1	*(1 - 1.3)*	0.7	*(0.7 - 0.9)*
Jump Height - Flight Time (cm)	**44.5 (6.4)**	2.8	*(2.6 - 3.4)*	3.1	*(2.9 - 3.8)*	2.7	*(2.5 - 3.3)*	3.5	*(3.2 - 4.3)*	2.8	*(2.6 - 3.4)*
Countermovement Depth (cm)	**44.3 (6.6)**	5.4	*(5 - 6.6)*	4.1	*(3.8 - 5)*	4.2	*(3.9 - 5.1)*	4.4	*(4 - 5.3)*	5.5	*(5.1 - 6.7)*
Eccentric Peak Force (N)	**2566 (406)**	4.3	*(4 - 5.2)*	4.3	*(4 - 5.2)*	4.1	*(3.8 - 4.9)*	5.6	*(5.2 - 6.9)*	4.3	*(3.9 - 5.2)*
Concentric Peak Force (N)	**2555 (395)**	3.4	*(3.2 - 4.1)*	2.9	*(2.6 - 3.5)*	3.9	*(3.6 - 4.8)*	4.2	*(3.9 - 5.2)*	3.4	*(3.1 - 4.1)*
Concentric Mean Force (N)	**1974 (272)**	2.0	*(1.9 - 2.4)*	1.7	*(1.5 - 2)*	2.0	*(1.8 - 2.4)*	2.3	*(2.1 - 2.8)*	2.0	*(1.9 - 2.5)*
Peak Landing Force (N)	**8165 (2072)**	11.6	*(10.7 - 14)*	13.5	*(12.4 - 16.3)*	10.4	*(9.6 - 12.6)*	13.1	*(12.1 - 16)*	11.8	*(10.9 - 14.3)*
Force at Zero Velocity (N)	**2534 (404)**	4.1	*(3.8 - 5)*	4.0	*(3.7 - 4.9)*	4.0	*(3.7 - 4.9)*	5.2	*(4.8 - 6.4)*	4.1	*(3.8 - 5)*
Force at Peak Power (N)	**2042 (279)**	2.1	*(2 - 2.6)*	2.7	*(2.5 - 3.2)*	2.1	*(1.9 - 2.5)*	2.2	*(2 - 2.7)*	2.2	*(2 - 2.6)*
Eccentric Peak Power (W)	**2481 (613)**	9.0	*(8.3 - 10.9)*	10.3	*(9.5 - 12.4)*	8.9	*(8.2 - 10.7)*	10.4	*(9.6 - 12.6)*	9.2	*(8.4 - 11.1)*
Concentric Peak Power (W)	**5088 (754)**	4.4	*(4 - 5.3)*	3.2	*(3 - 3.9)*	3.9	*(3.6 - 4.8)*	4.8	*(4.4 - 5.8)*	4.5	*(4.1 - 5.4)*
Eccentric Mean Power (W)	**862 (134)**	5.9	*(5.4 - 7.1)*	6.7	*(6.2 - 8.1)*	4.9	*(4.5 - 6)*	7.3	*(6.7 - 8.8)*	6.0	*(5.5 - 7.2)*
Concentric Mean Power (W)	**2896 (459)**	4.7	*(4.3 - 5.6)*	3.8	*(3.5 - 4.6)*	4.5	*(4.1 - 5.4)*	5.7	*(5.2 - 6.9)*	4.7	*(4.3 - 5.7)*
Eccentric Peak Velocity ($m.s^{-1}$)	**1.6 (0.19)**	4.9	*(4.5 - 5.9)*	6.2	*(5.7 - 7.5)*	4.3	*(4 - 5.3)*	6.0	*(5.5 - 7.3)*	4.9	*(4.5 - 6)*
Concentric Peak Velocity ($m.s^{-1}$)	**2.8 (0.2)**	3.1	*(2.9 - 3.8)*	2.4	*(2.2 - 2.9)*	2.7	*(2.5 - 3.3)*	3.5	*(3.2 - 4.3)*	3.2	*(2.9 - 3.9)*
Eccentric Deceleration RFD ($N.s^{-1}$)	**8683 (3434)**	12.1	*(11.1 - 14.6)*	11.4	*(10.5 - 13.8)*	11.6	*(10.7 - 14)*	16.6	*(15.3 - 20.1)*	12.1	*(11.2 - 14.7)*
Concentric Impulse 100ms (Ns)	**131 (28)**	5.0	*(4.6 - 6.1)*	5.3	*(4.9 - 6.4)*	5.7	*(5.3 - 6.9)*	6.4	*(5.9 - 7.8)*	5.0	*(4.6 - 6.1)*
Landing RFD ($N.s^{-1}$)	**539272 (240965)**	28.0	*(25.8 - 33.8)*	28.9	*(26.6 - 35)*	19.8	*(18.2 - 23.9)*	30.2	*(27.8 - 36.7)*	28.5	*(26.2 - 34.5)*
Eccentric Duration (ms)	**521 (84)**	5.0	*(4.6 - 6.1)*	5.6	*(5.2 - 6.8)*	5.0	*(4.6 - 6)*	5.8	*(5.4 - 7.1)*	5.1	*(4.7 - 6.2)*
Eccentric Deceleration Phase Duration (s)	**0.19 (0.036)**	5.6	*(5.1 - 6.7)*	4.9	*(4.5 - 6)*	5.5	*(5.1 - 6.7)*	7.8	*(7.1 - 9.4)*	5.6	*(5.2 - 6.8)*
Concentric Duration (ms)	**283 (33)**	3.2	*(3 - 3.9)*	2.7	*(2.5 - 3.3)*	2.6	*(2.4 - 3.2)*	3.0	*(2.8 - 3.7)*	3.3	*(3 - 4)*
Movement Start to Peak Force (s)	**0.53 (0.104)**	9.9	*(9.1 - 11.9)*	10.7	*(9.8 - 12.9)*	8.3	*(7.6 - 10)*	10.2	*(9.4 - 12.4)*	10.1	*(9.3 - 12.2)*
Movement Start to Peak Power (s)	**0.74 (0.111)**	4.2	*(3.9 - 5.1)*	4.4	*(4.1 - 5.4)*	4.1	*(3.8 - 4.9)*	4.9	*(4.5 - 5.9)*	4.3	*(3.9 - 5.2)*
Flight Time/ Contraction Time Ratio	**0.76 (0.103)**	4.3	*(4 - 5.2)*	4.9	*(4.5 - 5.9)*	4.4	*(4.1 - 5.3)*	5.7	*(5.2 - 6.9)*	4.4	*(4 - 5.3)*
Eccentric/ Concentric Mean Force (%)	**51.5 (3.4)**	1.7	*(1.6 - 2.1)*	1.7	*(1.5 - 2)*	1.8	*(1.6 - 2.2)*	2.3	*(2.1 - 2.8)*	1.7	*(1.6 - 2.1)*

Abbreviations: CV, coefficient of variation; $Mean_3$, mean output across 3 jump trials; Mon, Monday; Tue, Tuesday; Thu, Thursday

Table 4.3 - Inter-day absolute reliability (CV) and 95% confidence intervals of countermovement jump variables using $Best_{JH}$

Variable	*Mean (±SD)*	*Condition 1 Mon-Tue*		*Condition 2 Mon-Thu*		*Condition 3 Tue-Thu*		*Condition 4 Mon-Mon*		*Condition 5 Mon-Tue-Thu*	
Body Weight (kg)	**102.8 (12)**	0.7	*(0.7 - 0.9)*	0.9	*(0.8 - 1.1)*	0.9	*(0.8 - 1.1)*	1.1	*(1 - 1.3)*	0.7	*(0.7 - 0.9)*
Jump Height - Flight Time (cm)	**45.4 (6.3)**	2.7	*(2.5 - 3.3)*	3.0	*(2.8 - 3.7)*	2.6	*(2.4 - 3.1)*	3.7	*(3.4 - 4.6)*	2.8	*(2.6 - 3.4)*
Countermovement Depth (cm)	**44.2 (6.6)**	7.6	*(7 - 9.2)*	5.9	*(5.4 - 7.1)*	5.6	*(5.2 - 6.8)*	6.4	*(5.9 - 7.8)*	7.7	*(7.1 - 9.3)*
Eccentric Peak Force (N)	**2582 (405)**	5.4	*(5 - 6.5)*	5.2	*(4.7 - 6.2)*	6.1	*(5.6 - 7.4)*	7.2	*(6.6 - 8.7)*	5.5	*(5.1 - 6.6)*
Concentric Peak Force (N)	**2567 (396)**	3.7	*(3.4 - 4.4)*	3.9	*(3.6 - 4.7)*	5.3	*(4.9 - 6.4)*	6.3	*(5.8 - 7.6)*	3.7	*(3.4 - 4.5)*
Concentric Mean Force (N)	**1994 (277)**	2.6	*(2.4 - 3.2)*	1.9	*(1.7 - 2.3)*	2.4	*(2.2 - 3)*	3.2	*(2.9 - 3.8)*	2.7	*(2.5 - 3.2)*
Peak Landing Force (N)	**8539 (2349)**	20.4	*(18.8 - 24.6)*	21.5	*(19.8 - 26)*	15.8	*(14.6 - 19.2)*	21.8	*(20.1 - 26.5)*	19.6	*(18.1 - 23.8)*
Force at Zero Velocity (N)	**2548 (402)**	5.1	*(4.7 - 6.2)*	4.7	*(4.3 - 5.7)*	6.0	*(5.5 - 7.2)*	6.3	*(5.8 - 7.7)*	5.2	*(4.8 - 6.3)*
Force at Peak Power (N)	**2058 (288)**	3.4	*(3.1 - 4)*	3.8	*(3.5 - 4.6)*	3.0	*(2.7 - 3.6)*	4.7	*(4.3 - 5.7)*	3.4	*(3.1 - 4.1)*
Eccentric Peak Power (W)	**2542 (636)**	13.4	*(12.4 - 16.2)*	12.3	*(11.3 - 14.9)*	11.4	*(10.5 - 13.8)*	16.5	*(15.2 - 20.1)*	13.5	*(12.5 - 16.4)*
Concentric Peak Power (W)	**5150 (746)**	6.1	*(5.7 - 7.4)*	4.4	*(4.1 - 5.4)*	5.0	*(4.6 - 6.1)*	6.6	*(6.1 - 8)*	6.1	*(5.7 - 7.4)*
Eccentric Mean Power (W)	**873 (142)**	8.0	*(7.4 - 9.7)*	7.7	*(7.1 - 9.3)*	6.2	*(5.7 - 7.5)*	10.0	*(9.2 - 12.1)*	8.0	*(7.4 - 9.7)*
Concentric Mean Power (W)	**2942 (455)**	6.6	*(6 - 7.9)*	4.5	*(4.1 - 5.4)*	5.6	*(5.1 - 6.7)*	7.5	*(6.9 - 9.1)*	6.5	*(6 - 7.9)*
Eccentric Peak Velocity ($m.s^{-1}$)	**1.7 (0.2)**	7.4	*(6.8 - 8.9)*	7.1	*(6.5 - 8.6)*	5.8	*(5.4 - 7)*	8.3	*(7.6 - 10)*	7.4	*(6.9 - 9)*
Concentric Peak Velocity ($m.s^{-1}$)	**2.8 (0.2)**	4.4	*(4 - 5.2)*	3.1	*(2.8 - 3.7)*	3.4	*(3.1 - 4.1)*	4.5	*(4.1 - 5.4)*	4.3	*(4 - 5.2)*
Eccentric Deceleration RFD ($N.s^{-1}$)	**8848 (3380)**	16.8	*(15.5 - 20.3)*	13.6	*(12.6 - 16.5)*	17.5	*(16.1 - 21.1)*	21.6	*(19.9 - 26.3)*	17.1	*(15.8 - 20.7)*
Concentric Impulse 100ms (Ns)	**133 (28)**	6.6	*(6.1 - 7.9)*	5.8	*(5.4 - 7.1)*	7.5	*(6.9 - 9.1)*	7.4	*(6.8 - 9)*	6.7	*(6.1 - 8.1)*
Landing RFD ($N.s^{-1}$)	**604117 (273813)**	46.5	*(42.9 - 56)*	41.8	*(38.5 - 50.6)*	34.6	*(31.9 - 41.9)*	45.8	*(42.1 - 55.6)*	47.0	*(43.3 - 56.8)*
Eccentric Duration (ms)	**513 (85)**	6.0	*(5.5 - 7.2)*	5.7	*(5.3 - 6.9)*	5.4	*(4.9 - 6.5)*	8.5	*(7.8 - 10.4)*	6.0	*(5.5 - 7.3)*
Eccentric Deceleration Phase Duration (s)	**0.19 (0.033)**	8.2	*(7.5 - 9.8)*	5.6	*(5.2 - 6.8)*	8.1	*(7.5 - 9.9)*	11.0	*(10.1 - 13.3)*	8.3	*(7.6 - 10)*
Concentric Duration (ms)	**280 (33)**	3.9	*(3.6 - 4.7)*	3.3	*(3 - 3.9)*	3.0	*(2.8 - 3.6)*	3.5	*(3.2 - 4.3)*	4.0	*(3.6 - 4.8)*
Movement Start to Peak Force (s)	**0.52 (0.098)**	13.7	*(12.6 - 16.5)*	10.4	*(9.6 - 12.6)*	11.9	*(11 - 14.4)*	9.9	*(9.2 - 12.1)*	13.9	*(12.8 - 16.8)*
Movement Start to Peak Power (s)	**0.73 (0.111)**	4.6	*(4.3 - 5.6)*	4.4	*(4 - 5.3)*	4.3	*(3.9 - 5.2)*	6.8	*(6.3 - 8.3)*	4.7	*(4.3 - 5.7)*
Flight Time/ Contraction Time Ratio	**0.78 (0.104)**	4.8	*(4.5 - 5.8)*	4.6	*(4.2 - 5.5)*	4.5	*(4.2 - 5.5)*	7.3	*(6.7 - 8.8)*	4.9	*(4.5 - 5.9)*
Eccentric/ Concentric Mean Force (%)	**51 (3.4)**	2.4	*(2.2 - 2.9)*	1.8	*(1.7 - 2.2)*	2.3	*(2.1 - 2.8)*	3.2	*(3 - 3.9)*	2.4	*(2.2 - 2.9)*

Abbreviations: CV, coefficient of variation; $Best_{JH}$, single output for each variable from the trial with the highest jump; Mon, Monday; Tue, Tuesday; Thu, Thursday

Table 4.4 - Inter-day relative reliability (ICC) and 95% confidence intervals of countermovement jump variables using $Mean_3$

Variable	*Condition 1 Mon-Tue*		*Condition 2 Mon-Thu*		*Condition 3 Tue-Thu*		*Condition 4 Mon-Mon*		*Condition 5 Mon-Tue-Thu*	
Body Weight (kg)	0.997	*(0.992-0.999)*	0.997	*(0.992-0.998)*	0.995	*(0.964-0.998)*	0.995	*(0.991-0.998)*	0.997	*(0.994-0.999)*
Jump Height - Flight Time (cm)	0.97	*(0.92-0.99)*	0.98	*(0.96-0.99)*	0.98	*(0.93-0.99)*	0.96	*(0.88-0.98)*	0.98	*(0.97-0.99)*
Countermovement Depth (cm)	0.95	*(0.9-0.98)*	0.97	*(0.93-0.98)*	0.97	*(0.92-0.98)*	0.96	*(0.92-0.98)*	0.97	*(0.95-0.99)*
Eccentric Peak Force (N)	0.94	*(0.56-0.98)*	0.97	*(0.93-0.98)*	0.94	*(0.65-0.98)*	0.94	*(0.88-0.97)*	0.97	*(0.9-0.99)*
Concentric Peak Force (N)	0.96	*(0.6-0.99)*	0.98	*(0.96-0.99)*	0.95	*(0.77-0.98)*	0.96	*(0.92-0.98)*	0.97	*(0.92-0.99)*
Concentric Mean Force (N)	0.99	*(0.95-0.99)*	0.99	*(0.99-1)*	0.99	*(0.94-1)*	0.98	*(0.95-0.99)*	0.99	*(0.98-1)*
Peak Landing Force (N)	0.90	*(0.79-0.95)*	0.87	*(0.75-0.94)*	0.90	*(0.81-0.95)*	0.89	*(0.75-0.95)*	0.92	*(0.86-0.96)*
Force at Zero Velocity (N)	0.95	*(0.66-0.98)*	0.97	*(0.94-0.99)*	0.95	*(0.72-0.98)*	0.95	*(0.9-0.98)*	0.97	*(0.92-0.99)*
Force at Peak Power (N)	0.99	*(0.97-0.99)*	0.98	*(0.96-0.99)*	0.98	*(0.94-0.99)*	0.98	*(0.96-0.99)*	0.99	*(0.98-0.99)*
Eccentric Peak Power (W)	0.92	*(0.8-0.97)*	0.93	*(0.85-0.96)*	0.90	*(0.66-0.96)*	0.92	*(0.83-0.96)*	0.94	*(0.88-0.97)*
Concentric Peak Power (W)	0.94	*(0.81-0.98)*	0.97	*(0.95-0.99)*	0.95	*(0.84-0.98)*	0.93	*(0.78-0.97)*	0.97	*(0.94-0.99)*
Eccentric Mean Power (W)	0.94	*(0.87-0.97)*	0.93	*(0.85-0.96)*	0.93	*(0.79-0.97)*	0.90	*(0.8-0.95)*	0.95	*(0.91-0.98)*
Concentric Mean Power (W)	0.94	*(0.78-0.98)*	0.97	*(0.94-0.99)*	0.95	*(0.78-0.98)*	0.93	*(0.82-0.97)*	0.97	*(0.92-0.98)*
Eccentric Peak Velocity ($m.s^{-1}$)	0.92	*(0.82-0.96)*	0.89	*(0.78-0.94)*	0.92	*(0.72-0.97)*	0.89	*(0.78-0.95)*	0.94	*(0.88-0.97)*
Concentric Peak Velocity ($m.s^{-1}$)	0.89	*(0.7-0.95)*	0.95	*(0.9-0.98)*	0.91	*(0.74-0.96)*	0.88	*(0.72-0.95)*	0.94	*(0.88-0.97)*
Eccentric Deceleration RFD ($N.s^{-1}$)	0.94	*(0.71-0.98)*	0.97	*(0.94-0.99)*	0.95	*(0.84-0.98)*	0.95	*(0.9-0.97)*	0.97	*(0.93-0.99)*
Concentric Impulse 100ms (Ns)	0.96	*(0.84-0.99)*	0.98	*(0.95-0.99)*	0.96	*(0.85-0.98)*	0.96	*(0.92-0.98)*	0.98	*(0.95-0.99)*
Landing RFD ($N.s^{-1}$)	0.83	*(0.67-0.92)*	0.84	*(0.68-0.92)*	0.88	*(0.76-0.94)*	0.86	*(0.72-0.93)*	0.89	*(0.81-0.94)*
Eccentric Duration (ms)	0.96	*(0.92-0.98)*	0.91	*(0.81-0.95)*	0.94	*(0.88-0.97)*	0.91	*(0.81-0.96)*	0.96	*(0.92-0.98)*
Eccentric Deceleration Phase Duration (s)	0.94	*(0.77-0.98)*	0.96	*(0.92-0.98)*	0.95	*(0.86-0.98)*	0.91	*(0.81-0.95)*	0.96	*(0.93-0.98)*
Concentric Duration (ms)	0.97	*(0.93-0.98)*	0.97	*(0.95-0.99)*	0.97	*(0.95-0.99)*	0.96	*(0.92-0.98)*	0.98	*(0.96-0.99)*
Movement Start to Peak Force (s)	0.86	*(0.73-0.93)*	0.80	*(0.61-0.9)*	0.87	*(0.74-0.94)*	0.84	*(0.67-0.92)*	0.89	*(0.81-0.94)*
Movement Start to Peak Power (s)	0.97	*(0.93-0.98)*	0.93	*(0.87-0.97)*	0.96	*(0.91-0.98)*	0.93	*(0.85-0.96)*	0.97	*(0.94-0.98)*
Flight Time/ Contraction Time Ratio	0.95	*(0.9-0.98)*	0.95	*(0.91-0.98)*	0.95	*(0.91-0.98)*	0.92	*(0.83-0.96)*	0.97	*(0.94-0.98)*
Eccentric/ Concentric Mean Force (%)	0.96	*(0.88-0.98)*	0.97	*(0.94-0.98)*	0.96	*(0.92-0.98)*	0.92	*(0.77-0.97)*	0.97	*(0.95-0.99)*

Abbreviations: ICC, intra-class correlation coefficient; $Mean_3$, mean output across 3 jump trials; Mon, Monday; Tue, Tuesday; Thu, Thursday

Table 4.5 - Inter-day relative reliability (ICC) and 95% confidence intervals of countermovement jump variables using $Best_{JH}$ –

Variable	Condition 1 Mon-Tue		Condition 2 Mon-Thu		Condition 3 Tue-Thu		Condition 4 Mon-Mon		Condition 5 Mon-Tue-Thu	
Body Weight (kg)	0.997	*(0.992-0.999)*	0.997	*(0.992-0.998)*	0.995	*(0.964-0.998)*	0.995	*(0.991-0.998)*	0.997	*(0.994-0.999)*
Jump Height - Flight Time (cm)	0.97	*(0.91-0.99)*	0.98	*(0.95-0.99)*	0.98	*(0.92-0.99)*	0.95	*(0.88-0.98)*	0.98	*(0.97-0.99)*
Countermovement Depth (cm)	0.89	*(0.77-0.94)*	0.93	*(0.86-0.96)*	0.93	*(0.84-0.97)*	0.93	*(0.85-0.96)*	0.94	*(0.9-0.97)*
Eccentric Peak Force (N)	0.91	*(0.38-0.97)*	0.94	*(0.89-0.97)*	0.90	*(0.66-0.96)*	0.89	*(0.79-0.95)*	0.94	*(0.86-0.98)*
Concentric Peak Force (N)	0.94	*(0.35-0.98)*	0.97	*(0.93-0.98)*	0.92	*(0.73-0.97)*	0.92	*(0.83-0.96)*	0.96	*(0.9-0.98)*
Concentric Mean Force (N)	0.98	*(0.95-0.99)*	0.99	*(0.98-1)*	0.98	*(0.95-0.99)*	0.97	*(0.92-0.98)*	0.99	*(0.98-0.99)*
Peak Landing Force (N)	0.73	*(0.45-0.86)*	0.80	*(0.6-0.9)*	0.83	*(0.66-0.91)*	0.77	*(0.44-0.89)*	0.86	*(0.74-0.92)*
Force at Zero Velocity (N)	0.93	*(0.54-0.98)*	0.96	*(0.91-0.98)*	0.91	*(0.72-0.96)*	0.92	*(0.84-0.96)*	0.95	*(0.89-0.98)*
Force at Peak Power (N)	0.97	*(0.94-0.99)*	0.96	*(0.92-0.98)*	0.97	*(0.93-0.99)*	0.93	*(0.86-0.97)*	0.98	*(0.96-0.99)*
Eccentric Peak Power (W)	0.86	*(0.63-0.94)*	0.87	*(0.73-0.93)*	0.88	*(0.57-0.95)*	0.78	*(0.55-0.89)*	0.91	*(0.83-0.96)*
Concentric Peak Power (W)	0.92	*(0.83-0.96)*	0.95	*(0.90-0.98)*	0.94	*(0.88-0.97)*	0.87	*(0.68-0.94)*	0.96	*(0.92-0.98)*
Eccentric Mean Power (W)	0.88	*(0.73-0.94)*	0.90	*(0.8-0.95)*	0.90	*(0.69-0.96)*	0.82	*(0.64-0.91)*	0.93	*(0.86-0.96)*
Concentric Mean Power (W)	0.91	*(0.79-0.96)*	0.95	*(0.91-0.98)*	0.93	*(0.83-0.97)*	0.87	*(0.73-0.94)*	0.95	*(0.91-0.98)*
Eccentric Peak Velocity ($m.s^{-1}$)	0.83	*(0.63-0.92)*	0.85	*(0.7-0.93)*	0.88	*(0.61-0.95)*	0.80	*(0.59-0.9)*	0.90	*(0.81-0.95)*
Concentric Peak Velocity ($m.s^{-1}$)	0.83	*(0.67-0.92)*	0.92	*(0.85-0.96)*	0.89	*(0.78-0.95)*	0.82	*(0.62-0.92)*	0.92	*(0.86-0.96)*
Eccentric Deceleration RFD ($N.s^{-1}$)	0.91	*(0.62-0.96)*	0.95	*(0.89-0.97)*	0.90	*(0.76-0.95)*	0.88	*(0.75-0.94)*	0.94	*(0.88-0.97)*
Concentric Impulse 100ms (Ns)	0.95	*(0.84-0.98)*	0.97	*(0.93-0.98)*	0.94	*(0.83-0.97)*	0.94	*(0.88-0.97)*	0.97	*(0.93-0.98)*
Landing RFD ($N.s^{-1}$)	0.73	*(0.46-0.86)*	0.76	*(0.51-0.88)*	0.76	*(0.53-0.88)*	0.81	*(0.61-0.91)*	0.82	*(0.67-0.9)*
Eccentric Duration (ms)	0.93	*(0.87-0.97)*	0.91	*(0.82-0.96)*	0.94	*(0.88-0.97)*	0.81	*(0.61-0.91)*	0.95	*(0.91-0.97)*
Eccentric Deceleration Phase Duration (s)	0.87	*(0.63-0.94)*	0.95	*(0.9-0.97)*	0.89	*(0.74-0.95)*	0.82	*(0.64-0.91)*	0.93	*(0.86-0.97)*
Concentric Duration (ms)	0.94	*(0.89-0.97)*	0.96	*(0.93-0.98)*	0.97	*(0.94-0.99)*	0.95	*(0.9-0.98)*	0.97	*(0.95-0.99)*
Movement Start to Peak Force (s)	0.73	*(0.47-0.86)*	0.83	*(0.65-0.91)*	0.76	*(0.52-0.88)*	0.86	*(0.71-0.93)*	0.84	*(0.71-0.91)*
Movement Start to Peak Power (s)	0.95	*(0.9-0.97)*	0.94	*(0.88-0.97)*	0.96	*(0.91-0.98)*	0.86	*(0.71-0.93)*	0.97	*(0.94-0.98)*
Flight Time/ Contraction Time Ratio	0.94	*(0.87-0.97)*	0.96	*(0.91-0.98)*	0.94	*(0.87-0.97)*	0.87	*(0.73-0.94)*	0.96	*(0.93-0.98)*
Eccentric/ Concentric Mean Force (%)	0.93	*(0.85-0.97)*	0.96	*(0.93-0.98)*	0.94	*(0.89-0.97)*	0.86	*(0.67-0.94)*	0.96	*(0.93-0.98)*

Abbreviations: ICC, intra-class correlation coefficient; $Best_{JH}$, single output for each variable from the trial with the highest; Mon, Monday; Tue, Tuesday; Thu, Thursday

4.6. Discussion

The present study is a comprehensive analysis of the reliability of 86 CMJ kinetic variables in professional rugby union players, using $Mean_3$ and $Best_{JH}$ across 5 different inter-day conditions. This 'ecologically valid' data, collected within a professional team environment during pre-season, provides extensive reliability reference data for a wide range of CMJ variables. There are also several other important findings for practitioners and researchers. Absolute inter-day reliability (CV) was consistently lower for variables calculated using $Mean_3$ compared with $Best_{JH}$, a trend evident at both the upper and lower ends of the reliability spectrum. The CVs were lower than in previous studies that employed similar methodology (Gathercole, Sporer, et al., 2015a; Nibali et al., 2015), which may be related to differences in protocols, specifically the testing environment, training age of the athletes and testing schedule. Importantly, there were no meaningful differences in ICC between conditions, indicating high relative reliability independent of test/re-test period, suggesting that any of the combinations could be implemented depending on the constraints of different team and sport settings. This work also provides a framework for other practitioners to establish 'ecological' validity within their own environments; this type of cohort specific information is best practice in understanding specific measurement characteristics to inform practice.

We examined a combination of protocols (i.e., Conditions 1-5; see **Table 4.1**) to understand differences in reliability in various temporal combinations that might be feasible within a training week. While small changes (i.e., ~1-3%) were observed in mean performance across several variables throughout the testing week likely reflecting fluctuations in residual fatigue and recovery (Gathercole, Stellingwerff, et al., 2015b), there were no meaningful differences in absolute reliability between different inter-day test combinations. These findings indicate that reliability can be validly assessed within the typical training and recovery cycles of the first week of pre-season training.

In professional team sport settings, it is important that test protocols are rapid and easy to implement, with low athlete burden, but this should not be at the expense of meaningfulness of the test results. For example, based on the findings of a recent review (Claudino et al., 2017), implementing a single trial CMJ protocol would reduce the practitioner's ability to identify meaningful changes in most variables, compared to mean results from multiple (3-6) trials. Aligning with this, we found that CVs for the $Mean_3$ data were consistently lower than or equal to $Best_{JH}$ in all variables, which is quite astounding given the 430 data points examined (i.e., 86 variables across 5 conditions). Nonetheless, we cannot exclude the potential utility of the $Best_{JH}$ method as inter-day reliability (noise) of a variable, needs to be examined in the context of its sensitivity (signal) in ecologically relevant conditions, to determine whether it will be valuable in monitoring changes in representative athlete cohorts. Previous studies have commonly examined the reliability of performance tests, including the CMJ, using a threshold for 'adequate' absolute reliability, such as CV ≤ 10% (Cormack, Newton, Mcguigan, et al., 2008a). By setting an arbitrary reliability threshold, and doing so independent of measured signal, may mistakenly eliminate some of the most valuable data (Atkinson & Nevill, 1998). Indeed, a variable with a higher CV may be extremely useful if particularly sensitive to changes in athlete status (i.e., training/competition stimuli result in changes greater than the inter-day CV) (Cormack, Newton, & McGuigan, 2008; Ryan et al., 2019b). Conversely, a variable with a very low CV may be of limited use if it remains stable in response to meaningful interventions and fails to reflect underlying adaptations (Cormack, Newton, McGuigan, & Cormie, 2008; Kraufvelin, 1998). Therefore, determining inclusion/exclusion and classifying the meaningfulness of variables based on reliability alone may lead to erroneous conclusions.

A number of CMJ variables have been shown to be sensitive to changes in neuromuscular status associated with fatigue (Cormack, Newton, & McGuigan, 2008; Cormack, Newton, McGuigan, & Cormie, 2008), chronic adaptations to training (Cormie et al., 2009b; Cormie et al., 2010), prior injury status (Cohen, 2020; Hart et al., 2019) and performance changes in competition (Mooney et al., 2013). These variables provide information about changes in how a CMJ was performed (i.e., jump strategy) and have been observed often in the absence of meaningful changes in jump height (Cohen, 2020; Cormie et al., 2009b; Nibali et al., 2015). Although these variables appear to be more sensitive to the effects of loading or injury, they also tend to display higher CV than other commonly studied CMJ variables (Cohen, 2020). An important outcome of the present study was the lower CV in a number of these variables (e.g., eccentric deceleration rate of force development, eccentric duration and flight time: contraction time ratio) compared with previous studies (Gathercole, Sporer, et al., 2015a; Heishman et al., 2018; Nibali et al., 2015), alongside similar CV (~3%) for jump height.

The flight time: contraction time ratio (FTCT) is a jump strategy variable sensitive to neuromuscular changes following competition (Cormack, Newton, & McGuigan, 2008; Gathercole, Stellingwerff, et al., 2015b) and the time-course for recovery post-competition (Cormack, Newton, McGuigan, & Cormie, 2008), with fluctuations primarily driven by changes in eccentric and concentric duration (Cohen, 2020). Using $Mean_3$, our results show a CV of 4.4% (Condition 5 – $Monday_1$ – Tuesday – Thursday) for FTCT, which is similar to that reported by Gathercole et al (Gathercole, Sporer, et al., 2015a) (CV=5.2%) when using the mean of the most consistent 4 out of 6 jumps (based on the mean eccentric and concentric power/time) in elite snowboard-cross athletes. Conversely, Heishman et al., (Heishman et al., 2018) reported greater variability in FTCT (CV=8.3%) when using the mean of 3 jumps from 2 testing sessions, in Division I basketball athletes. Heishman et al., (Heishman et al., 2018) conducted these 2 tests with at least 7 days separating them during a normal training (presumably in-season) period, whereas Gathercole et al., (Gathercole, Sporer, et al., 2015a) conducted 3 tests over 6 days, each testing day separated by a recovery day, outside of competition times, similar to our work. This suggests that longer periods between tests (i.e., in the vicinity of 14 days) and testing schedule could increase variability, while negligible variation exists in our 5 conditions examined over the course of 8 days of pre-season.

Eccentric deceleration rate of force development (EDRFD) is another strategy variable that has generated considerable interest in monitoring athletes' responses to training, assessing improvements in jump performance (Kijowksi et al., 2015; Laffaye & Wagner, 2013; Nibali et al., 2015) and during rehabilitation (Cohen, 2020; Hart et al., 2019). Inter-day EDRFD CV's (using $Mean_3$) ranged from 11.4% to 16.6% in our study, which is lower than previous work (Heishman et al., 2018; Nibali et al., 2015). Nibali et al., (Nibali et al., 2015) examined inter-day reliability in trials that were separated by a minimum of 24 hours and a maximum of 14 days, and reported their lowest $Mean_3$ CV's in professional athletes (CV ~17%), compared with cohorts from high-school (CV ~23%) and collegiate (CV ~19%) sports. Relative to previous work, the lower CV's we report for well-trained and familiarised athletes suggests that training age and experience with the testing protocol may impact inter-day reliability. Indeed, previous work has suggested that eccentric variables, such as EDRFD, may have been erroneously labelled as 'inherently unreliable' (Cohen, 2020). These authors suggested that variability during the eccentric phase may be related to inconsistent countermovement depth and eccentric velocity, arising from inconsistencies in technique. Our $Mean_3$ CVs for countermovement depth (4.1 – 5.5%) and eccentric peak velocity (4.3 – 6.2%) along with lower EDRFD CVs, show that reliability (of eccentric variables in particular) is not a fixed characteristic, and that the technique employed by an athlete stabilises with experience and training age.

Obtaining maximal effort in CMJ assessments is critical in obtaining valid results but is an often-overlooked aspect in assessing the reliability of a variable. As feedback of jump height achieved during testing improves CMJ performance (García-Ramos et al., 2020), we ensured that immediate analysis (i.e., provided by the software) was visible in the testing area, in an endeavour to create an environment of group encouragement aimed at increasing motivation, effort and subsequent performance (García-Ramos et al., 2020). In our experience in professional sport, immediate feedback to the athlete on their performance and creating a competitive environment drives more consistent maximal effort from the athletes, and this may have contributed to the lower CVs and higher ICCs observed for several variables, compared with previous work.

The higher CVs in high-school and collegiate athletes than in professional athletes, for all variables investigated reported by Nibali et al., (Nibali et al., 2015) supports the suggestion that lower training-age/non-professionals is associated with more noise in these measurements. In addition to the competitive environment, which can be created, our reliability data was collected in one professional team with both a high training age and level of familiarity with the CMJ, and as these factors likely influence measurement reliability, caution should be taken in generalising these findings.

The present study is a comprehensive analysis of inter-day reliability in professional team-sport athletes. We determined 'ecologically valid' reliability of 86 CMJ variables using $Mean_3$ and $Best_{JH}$ across 5 different inter-day combinations during the first 8 days of preseason. The comprehensive nature of this analysis improves current understanding of CMJ variable reliability in team-sport athletes and demonstrates lower CV (i.e., 'noise') in variables, particularly some eccentric ones, than previous studies. This suggests that protocol development and environment can have a substantial impact on reliability and should be carefully considered when using the CMJ for monitoring of neuromuscular changes.

It is important to emphasise that any reliability analysis simply establishes the 'noise' of a variable within a specific environment. Based on reliability data alone conclusions cannot be drawn as to the variables that are of most value in athlete monitoring, as this information needs to be combined with assessment of the typical variation over time ('signal') in a longitudinal analysis (Thorpe et al., 2015). Understanding the typical 'signal' in the context of the 'noise' – often presented as a 'signal-to-noise ratio' – can help establish which variables are most sensitive to training and competition stimuli (Currell & Jeukendrup, 2008). Accordingly, future studies should examine the signal and subsequent signal-to-noise ratio of a wide range of CMJ variables (Hopkins et al., 2001; Ryan et al., 2019b).

4.7. Practical applications

To achieve the most well-informed decision making around CMJ data, practitioners are strongly encouraged to perform their own cohort-specific analyses. We recommend conducting testing on any 2 days within or across the first week of pre-season, as reliability was relatively unaffected by training schedule or the specific combinations of assessments, when conducted prior to significant loading. This allows practitioners to select testing times that accommodate scheduling and other practical considerations, while still providing valid information around cohort specific reliability.

When developing test protocols, consideration should be given to achieving high athlete motivation. Creating competitive environments with immediate feedback (e.g., utilising ‘leaderboards and group encouragement) may help drive consistently high effort from the athletes. When interpreting results, it is also important to consider familiarisation with testing protocols and athlete training age, as younger and less familiarised athletes are unlikely to have developed a consistent technique. Once cohort specific reliability has been established, practitioners can then interpret the ongoing ‘signal’ within the context of the ‘noise’, which may help identify important changes in neuromuscular status over time. We acknowledge that some practitioners may not have the resource or capacity to conduct their own reliability assessments, in these cases the data presented herein can provide a comprehensive reference reliability for a wide range of CMJ variables.

Chapter 5

Study 2:

Sensitivity of Countermovement Jump variables in professional rugby union players within a playing season

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5.1. Preface

In Chapter 4 we conducted the first analysis of our framework – Establishing the Noise – elucidating the normal methodological and biological variation of a large group of CMJ variables. In this chapter, we move onto the second step of the framework, "Finding the Signal". To do this we build analyse the normal week-to-week variability of the same CMJ variables and combining both measures to create a signal-to-noise ratio (SNR). Examination of the 95% confidence intervals for both measures will help find the most sensitive CMJ measures.

5.2. Abstract

Purpose: To explore the measurement sensitivity of a wide range of countermovement jump (CMJ) variables to a full European professional rugby union season. A secondary purpose was to compare 3 different data treatment methods for the calculation of CMJ variables. Methods: Twenty-nine professional rugby union players (mean ± SD; age 24 ± 4 y, height 183.7 ± 8.0 cm, body mass 101.6 ± 10.7 kg) completed a minimum of 12 CMJ testing sessions on Thursdays – a day preceded by a rest day and a minimum of 96 h following a match – throughout a season. Measurement sensitivity, quantified by signal-to-noise ratio (SNR), was determined for 74 CMJ variables and was calculated by dividing the signal, (week-to-week variation expressed as a CV%) by the noise (inter-day test/re-test reliability expressed as CV%). We also identified variables which had no overlap between the 95% confidence intervals (CI) for the signal and the noise. The 3 data treatment methods for comparison were: 1) mean output across 3 jump trials ($Mean_3$), 2) single output from the trial with the highest jump ($Best_{JH}$); and 3) the trial with the highest flight time: contraction time ratio ($Best_{FTCT}$). Results: Most variables had a SNR >1.0 ($Mean_3$ = 60/74; $Best_{FTCT}$ = 59/74; $Best_{JH}$ = 48/74).

Fewer variables displayed a non-overlap of 95% CIs ($Mean_3$ = 23/60; $Best_{FTCT}$ = 22/59; $Best_{JH}$ = 16/48). Conclusions: Most CMJ variables during a professional rugby season demonstrated a signal that exceeded measured noise (SNR >1.0) and that using the $Mean_3$ or $Best_{FTCT}$ data treatment methods yields a greater number of variables considered sensitive within a season (i.e., SNR > 1.0) than when using $Best_{JH}$. We also recommend the calculation of the 95% CIs for both signal and noise, with non-overlap indicative of a greater probability that the responsiveness of the variable at team level (i.e., SNR) also applies at the individual level. As sensitivity analysis is cohort and environment specific, practitioners should conduct a sensitivity analysis using internal signal and noise data to inform their own monitoring protocols.

5.3. Introduction

Athletic performance testing profiles describe the maximal physical capacities of an athlete and are generally based on an individual's best performances in physical tests from a given period (e.g., pre-season) under favourable conditions (e.g., after a period of relative rest or planned supercompensation). In contrast, physical performance tests can also be conducted as part of more frequent athlete monitoring, where performance may not be optimal due to incomplete recovery from match and/or training demands. This type of monitoring does not necessarily seek to assess chronic adaptations to training (although it is not possible to completely differentiate from such adaptations), but to quantify changes in fitness and/or fatigue during training and competition periods (Coutts et al., 2018). In this context, data obtained from regular non-fatiguing performance tests, such as the countermovement jump (CMJ), are often used to quantify changes in performance 'readiness' (Enoka & Duchateau, 2016; Hulin et al., 2019) and specific physiological/mechanical qualities (Claudino et al., 2017; Cormack, Newton, McGuigan, & Cormie, 2008).

An essential step in qualifying any test for use in practice is to establish measurement characteristics of the variables to be monitored, including validity, reliability, and sensitivity (Coutts, 2014; Currell & Jeukendrup, 2008). Absolute inter-day test/re-test reliability (i.e., typical error as a CV%) is a commonly reported measurement that characterises the normal methodological and biological variation ('noise') of a test/variable (Atkinson & Nevill, 1998; Howarth et al., 2021). Similarly, individual week-to-week changes during a competitive season (i.e., 'signal') can be used to characterise measurement variability during the season (also commonly reported as a CV%). Signal can then be assessed with reference to the noise by combining these measures in a signal-to-noise ratio (SNR) (Currell & Jeukendrup, 2008; Howe et al., 2020), providing a means to quantify group-level sensitivity. This approach has previously been applied in team sport settings (Crowcroft et al., 2017; Mercer et al., 2021; Ryan et al., 2019b) to identify which monitoring variables are responsive to changes related to daily training and competition (Coutts, 2014).

The assessment of the CMJ and analysis of variables derived from the force-time curve is a popular method to describe athletes physical capacity (Cormie et al., 2009b; Cronin & Hansen, 2005) and their readiness to perform (Claudino et al., 2017; Cormack et al., 2013; Cormack, Newton, McGuigan, & Cormie, 2008). Increased availability and affordability of force platform systems, and analysis software, has improved the speed and accessibility of complex force-time data analyses. This has enabled practitioners to easily obtain a large number of variables within seconds of completing a test (Claudino et al., 2017; Gathercole, Sporer, et al., 2015a; Heishman et al., 2018). Whilst these advances in data availability can be useful, the large volume of information also creates variable selection and data management challenges for practitioners working in fast moving high-performance settings. These challenges are compounded when considering the need to process, interpret and synthesise data from several sources to inform decisions about training (Coutts et al., 2018). Accordingly, there is a need to reduce monitoring variable numbers to the most parsimonious group to assist practitioners with daily decision making (Coutts, 2014). Earlier work examining data reduction for monitoring CMJ force-time variables in athletes (Cormack, Newton, Mcguigan, et al., 2008a) aimed to qualify CMJ variables for further analysis of measurement characteristics by determining their absolute inter-day reliability, setting a cut-off value for inclusion of CV ≤10%. This resulted in 6/17 variables discarded, with 11 variables used in a future study examining the utility of CMJ assessments following the acute stress of an Australian football match (Cormack, Newton, & McGuigan, 2008). Although this data reduction technique has since been replicated (Claudino et al., 2017; Heishman et al., 2018), it is important to highlight that if the observed context-specific 'signal' is greater than the 'noise', variables with an inter-day CV >10% could still be useful in assessing changes in athlete status (Kraufvelin, 1998). Therefore, by setting arbitrary thresholds for 'acceptable' reliability (e.g., CV >10%) and using such cut-offs as inclusion criterion for monitoring processes, practitioners may erroneously discard useful variables or, conversely, include variables that are not sensitive or responsive to the inputs/loading patterns of the sport.

Typical CMJ assessment protocols in monitoring involve the athlete performing multiple trials (Claudino et al., 2017; Gathercole, Stellingwerff, et al., 2015b; Gathercole, Sporer, et al., 2015a). As such, the practitioner must determine whether to examine a single jump (e.g., 'best' trial), or the mean of multiple trials. This is an important data treatment decision which may impact the interpretation of results as it has been shown to result in differing inter-day reliability of variables (Howarth et al., 2021). Previous work indicates that using the mean of multiple CMJ trials results in greater sensitivity to acute stimuli than using the results from a single jump (Claudino et al., 2017; Kennedy & Drake, 2018). Three different data treatment methods have recently been used to evaluate the sensitivity of CMJ variables in professional basketball players (Mercer et al., 2021): mean of 3 jumps ($Mean_3$); data from the trial with the best jump height by flight time method ($Best_{JH}$), and; data from the trial with the best flight time: contraction time ratio ($Best_{FTCT}$). This analysis also determined that the mean of multiple trials yielded greater sensitivity than using either single-jump data treatment methods (Mercer et al., 2021).

To further explore the measurement characteristics of CMJ testing in rugby union players, we recently reported the reliability of 83 variables using two data treatment methods (i.e., $Mean_3$ and $Best_{JH}$) (Howarth et al., 2021). The inter-day CV's ('noise') observed were substantially lower than values reported in similar studies (Howarth et al., 2021), a finding attributed to athlete level, training and testing history, monitoring culture and athlete motivation. While inter-day reliability is commonly reported, there is a paucity of information exploring this measurement characteristic in the context of season variability, to better understand measurement sensitivity. For a variable to be relevant in athlete monitoring throughout a season, the 'signal' (i.e., the normal change in variables in response to the training/competition environment) needs to exceed the testing noise, and these testing characteristics should be determined within the context that they are intended to be used. Contextual factors that will influence changes in the variables being monitored (i.e., signal) include environment-specific factors, such as the proximity of assessments to competition and training, the competition schedule, and the positional/sport-specific demands placed on the athlete.

Therefore, the primary purpose of this study is to calculate the SNR of a wide range of CMJ variables to determine their sensitivity to the training and competition undertaken by professional rugby union players throughout a season. A secondary aim is to compare the sensitivity calculated using 3 different data treatment methods.

5.4. Methods

5.4.1. Experimental approach to the problem

Retrospective analysis was undertaken on data collected from a professional rugby union club across a full season (42 weeks). Normal methodological and biological variation (i.e., noise) of 83 CMJ variables was assessed through inter-day absolute reliability (CV%) using data from the second and fourth day of preseason, a combination of days where most variables had lower CVs for each data treatment method (Howarth et al., 2021). Countermovement jump data were collected as part of routine monitoring on Mondays and Thursdays through the remainder of the year. The team played 32 matches (3 preseason and 29 in-season matches), with no testing conducted during scheduled non-training weeks. In-season matches occurred once per week and were played on Fridays or Saturdays (**Figure 5.1**). All players selected in an upcoming Friday match did not test on the Thursday of that week.

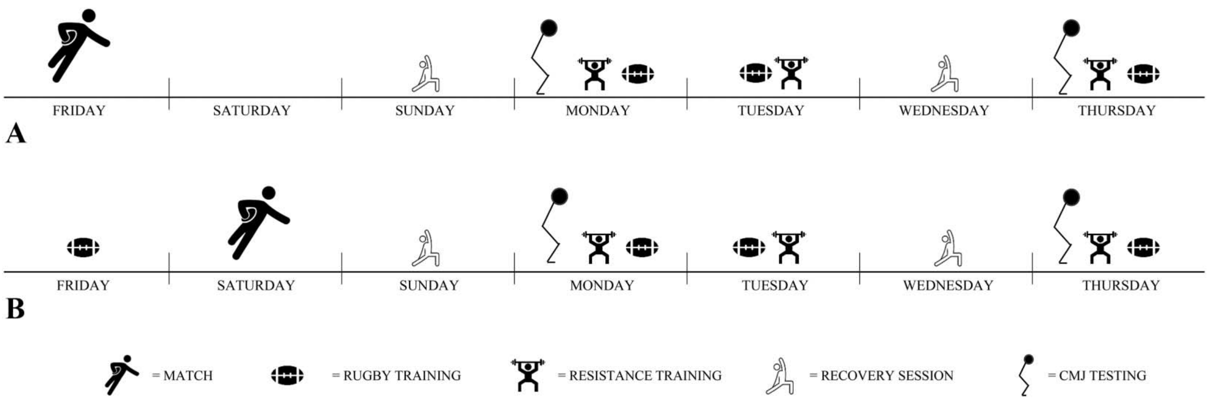

Figure 5.1 - Typical game and training week overview with scheduled jump testing.
A) Typical training week after a Friday game. Thursday CMJ assessment = 130–132 hours post-match. B) Typical training week after a Saturday game. Thursday CMJ assessment = 107–112 hours post-match. CMJ = countermovement jump.

Countermovement jump data collected on Thursdays aimed to assess "chronic" adaptations and low-frequency fatigue (Fowles, 2006; Gathercole, Sporer, et al., 2015a) and the results had limited influence of acute fatigue associated with the previous match (100 hours post-match) (Cormack, Newton, McGuigan, & Cormie, 2008; Gathercole, Sporer, et al., 2015a). In addition, all squad members had undertaken similar training for the 72 hours before this session, and the testing session always followed a rest day. These data were used to analyse the "signal" of CMJ variables throughout the season (**Figure 5.2**).

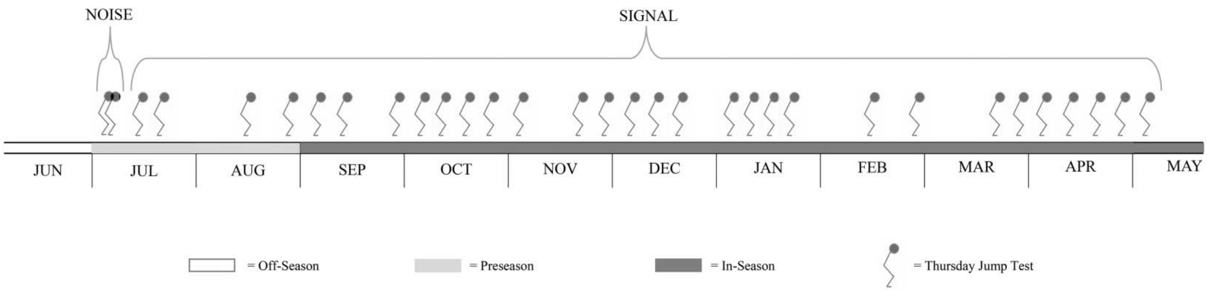

Figure 5.2 - Timeline of CMJ assessments across the 2018–2019 season for a Northern Hemisphere rugby union team.

Test/re-test reliability ("noise") calculated from the first week of preseason, and seasonal variability ("signal") calculated from 30 test points collected on Thursdays from the second week of preseason until the end of the regular season.

5.4.2. Subjects

The original cohort consisted of 43 professional male rugby union players who competed in the Pro 14 and European Challenge Cup competitions. We excluded data from 14 players who did not complete at least 12/30 CMJ testing sessions. We assessed all healthy players, meaning missed testing sessions were only due to injury, illness, or absence from the training environment (e.g., National Team assignment). The final analysis consisted of 29 players (mean ± SD; age 24 ± 4 y, height 183.7 ± 8.0 cm, body mass 101.6 ± 10.7 kg). All players provided written informed consent and volunteered to participate in this study. The study was approved by the Human Research Ethics Committee at the University of Technology Sydney (ETH19-3614).

5.4.3. Procedures

On testing days, players followed a previously described standardised warm-up (Howarth et al., 2021) before completing CMJ's during the same 15-minute period (i.e., individual testing time varied less than 15-min across the season) and was always conducted between 09:00 and 09:45.

CMJ's were performed on a dual force plate system (NMP ForceDecks FD-4000–Vald Performance, Brisbane, Australia) connected to a laptop computer (Dell Latitude E5440) using protocols previously described (Howarth et al., 2021). Analysis of the CMJ force-time curves and generation of variables was completed using ForceDecks software (v2.0.7418, Vald Performance, Brisbane, Australia) with methods described (Linthorne, 2001) and depicted elsewhere (Cohen et al., 2020; Howarth et al., 2021). Players received strong verbal encouragement during testing and immediate visual feedback post-CMJ on individual jump height (derived from flight time) through a digital display (ForceDecks Leaderboard v.2.0.7418, Vald Performance, Brisbane, Australia).

Each player was familiarised with the testing protocol (i.e., three repetitions of a single CMJ with hands on hips) having been involved in test/re-test evaluation at the beginning of pre-season along with prior exposure through this and other performance programs (Howarth et al., 2021). Every CMJ was observed by an experienced member of the performance staff and any jumps deviating from standard protocol (e.g., jumpers attempted to 'tuck' their legs during the flight phase, double jump/pre-jump, did not land on the force plates) were excluded, and another jump performed to ensure 3 acceptable trials.

5.4.4. Statistical analyses

From the ForceDecks system, 83 bilateral variables were exported for analysis. For variables that are calculated in both relative (i.e., per kg of body mass) and absolute values, only relative variables are presented, allowing for fluctuations in body mass throughout the season (Duthie et al., 2006), leaving 74 variables for analysis. Three different data treatment methods were used before further analysis: i) The mean for each variable across 3 jump trials ($Mean_3$)

(Claudino et al., 2017; Kennedy & Drake, 2018); ii) The outputs for each variable from the trial with the highest jump calculated by flight time ($Best_{JH}$) (Claudino et al., 2017; Kennedy & Drake, 2018); and, iii) The outputs for each variable from the trial with the highest flight time/ contraction time (FTCT) ratio ($Best_{FTCT}$) (Mercer et al., 2021).

Statistical analyses were carried out in R statistical software (R Development Core Team, 2010). All variables were log transformed to account for potential heteroscedasticity and skewness (Atkinson & Nevill, 1998). Variability within the season was calculated as the typical error using the pooled individual results derived from every week-to-week combination throughout the season, to establish the typical variability for the group (Crowcroft et al., 2017; Mercer et al., 2021; Ryan et al., 2019b), and represented as a CV% ± 95% confidence intervals (CI). The signal-to-noise ratio (SNR) was then calculated by dividing the CV% of each variable between each paired test across the whole season ('signal') by the test/re-test CV% between day 2 and 4 of the first week of the season ('noise'). As a secondary analysis, variables were evaluated for overlap of 95% CIs between 'signal' and 'noise' measures to further qualify sensitivity in a way which accounts for inferences being made based on sample size (Cumming & Finch, 2005; Wolfe & Cumming, 2004).

5.5. Results

Players completed an average of 19 of the 30 possible Thursday testing sessions throughout the season (range = 12-27 tests). Comparison of variable sensitivity between $Mean_3$, $Best_{FTCT}$ and $Best_{JH}$ are displayed in Figure 3. Most variables demonstrated a SNR >1.0 ($Mean_3$ = 60/74; $Best_{FTCT}$ = 59/74; $Best_{JH}$ = 48/74). $Mean_3$ (29/74) and $Best_{FTCT}$ (31/74) had comparable numbers of variables displaying their greatest sensitivity in that condition, where $Best_{JH}$ (14/74) was considerably lower.

Variables where 95% CIs did not overlap are shown in **Table 5.1** ($Mean_3$), **Table 5.2** ($Best_{JH}$) and **Table 5.3** ($Best_{FTCT}$). There were 6 variables which had 95% CIs that did not overlap for all data treatment methods: countermovement depth, eccentric duration, eccentric: concentric duration ratio, lower-limb stiffness, CMJ stiffness, and mean eccentric + concentric power: time. The SNR for landing impulse, force at peak power and braking phase duration/contraction time was ≤ 1.0 for all 3 data treatment methods. Full results for all variables can be found in Appendix 6 ($Mean_3$), Appendix 7 ($Best_{JH}$), and Appendix 8 ($Best_{FTCT}$).

Figure 5.3 - CMJ variables sorted from highest to lowest signal-to-noise ratio.

Grouped by phase of jump (i.e., eccentric, concentric, and landing, or as composite if not bound to one specific phase. Grey bars represent the mean absolute reliability (CV%) calculated from $Mean_3$, $Best_{JH}$ and $Best_{FTCT}$ results. RFD = rate of force development; RPD = rate of power development; * = variable and data treatment method with non-overlap of 95% confidence intervals; = average CV > 32%

Table 5.1 - Variables with non-overlap of 95% CI for signal and noise - Mean3

Variable	Signal CV (95% CI)	Noise CV (95% CI)	SNR	Mean	SD
Phase: Eccentric					
Countermovement Depth [cm]	10.1 (9.2-14.1)	5.4 (5-6.6)	1.9	44.6	6.7
Eccentric Duration [ms]	7.5 (6.8-10.4)	5.0 (4.6-6.1)	1.5	512	65
Phase: Concentric					
Concentric Impulse [Ns]	5.5 (5-7.7)	3.5 (3.2-4.2)	1.6	268	30
Concentric Impulse 100ms [Ns]	8.3 (7.5-11.6)	5.0 (4.6-6.1)	1.7	126	21
Concentric Impulse 50ms [Ns]	8.7 (7.9-12.1)	5.8 (5.4-7)	1.5	70	13
Concentric Mean Force-BM [N.kg $^{-1}$]	2.3 (2.1-3.3)	1.7 (1.6-2.1)	1.4	19.1	1.4
Concentric Mean Power-BM [W.kg $^{-1}$]	7.1 (6.4-9.9)	4.5 (4.1-5.4)	1.6	28	3.9
Concentric Peak Velocity [m.s $^{-1}$]	4.6 (4.2-6.4)	3.1 (2.9-3.8)	1.5	2.8	0.2
Concentric RPD 100ms-BM [W.s.kg $^{-1}$]	11.5 (10.4-16)	6.8 (6.3-8.2)	1.7	250	62
Concentric RPD 50ms-BM [W.s.kg $^{-1}$]	13.1 (11.9-18.3)	8.1 (7.5-9.8)	1.6	307	81
P2 Concentric Impulse-P1 Concentric Impulse Ratio	8.7 (7.8-12.1)	5.9 (5.4-7.1)	1.5	0.6	0.1
Velocity at Peak Power [m.s $^{-1}$]	4.9 (4.5-6.9)	3.2 (3-3.9)	1.5	2.5	0.2
Vertical Velocity at Takeoff [m.s $^{-1}$]	5.0 (4.5-6.9)	3.4 (3.1-4.1)	1.5	2.6	0.2
Phase: Landing					
Landing RFD 50ms [N.s $^{-1}$]	23.4 (21.2-32.7)	17.2 (15.9-20.8)	1.4	40,209	23,283
Phase: Composite					
CMJ Stiffness [N.m $^{-1}$]	12.0 (10.8-16.7)	6.6 (6.1-8)	1.8	5,879	1,172
Eccentric-Concentric Duration [%]	8.9 (8.1-12.4)	4.7 (4.4-5.7)	1.9	179	20
Eccentric-Concentric Mean Force Ratio [%]	2.3 (2.1-3.2)	1.7 (1.6-2.1)	1.4	52	3.6
Flight Time [ms]	1.9 (1.7-2.7)	1.4 (1.3-1.7)	1.4	602	40
Jump Height - Flight Time [cm]	3.8 (3.5-5.3)	2.8 (2.6-3.4)	1.4	44.6	5.9
Jump Height – Imp/Mom [cm]	10.2 (9.2-14.2)	6.9 (6.3-8.3)	1.5	36.0	6.4
Lower Limb Stiffness [N.m $^{-1}$]	12.9 (11.7-18)	7.5 (6.9-9)	1.7	5,524	1,211

Variable	Signal CV (95% CI)	Noise CV (95% CI)	SNR	Mean	SD
Mean Eccentric Concentric Power-Time [W.s $^{-1}$]	10.6 (9.6-14.8)	7.4 (6.8-8.9)	1.4	2,014	342
Total Work [J]	5.3 (4.8-7.5)	3.4 (3.1-4.1)	1.6	1,262	186

Table 5.2 - Variables with non-overlap of 95% CI for signal and noise - Best$_{JH}$

Variable	Signal CV (95% CI)	Noise CV (95% CI)	SNR	Mean	SD
Phase: Eccentric					
Countermovement Depth [cm]	13.8 (12.5-19.3)	7.6 (7-9.2)	1.8	44.8	7.0
Eccentric Acceleration Phase Duration [s]	12.6 (11.4-17.6)	7.9 (7.3-9.6)	1.6	0.3	0.0
Eccentric Duration [ms]	9.8 (8.9-13.7)	6.0 (5.5-7.2)	1.6	501	62
Time to Braking Phase [s]	23.8 (21.6-33.2)	16.3 (15-19.6)	1.5	0.2	0.0
Phase: Concentric					
Concentric Mean Force-BM [N.kg $^{-1}$]	3.2 (2.9-4.4)	2.4 (2.2-2.9)	1.3	19.2	1.4
Phase: Landing					
Jump Height FT Relative Peak Landing Force [N.cm]	30.8 (27.9-43)	19.9 (18.4-24)	1.5	189	59
Landing Net Peak Force-BM [N.kg $^{-1}$]	36.9 (33.4-51.5)	23.2 (21.3-27.9)	1.6	75	26
Peak Landing Force-BM [N.kg $^{-1}$]	28.6 (25.9-39.9)	20.1 (18.5-24.2)	1.4	85	26
Peak Landing Power [W]	30.6 (27.7-42.7)	22.1 (20.4-26.7)	1.4	25,049	8,309
Phase: Composite					
Contraction Time [ms]	6.6 (5.9-9.2)	4.3 (4-5.2)	1.5	787	86
CMJ Stiffness [N.m $^{-1}$]	15.0 (13.5-20.9)	8.7 (8-10.5)	1.7	5,872	1,218
Eccentric-Concentric Duration [%]	9.8 (8.9-13.7)	6.6 (6.1-8)	1.5	175	18.5
Flight Time-Contraction Time Ratio	6.6 (5.9-9.1)	4.8 (4.5-5.8)	1.4	0.8	0.1
Lower Limb Stiffness [N.m $^{-1}$]	15.2 (13.7-21.1)	9.8 (9-11.8)	1.6	5,519	1,265
Mean Eccentric Concentric Power-Time [W.s $^{-1}$]	13.0 (11.7-18.1)	8.9 (8.2-10.7)	1.5	2,083	360
Movement Start to Peak Power [s]	7.0 (6.4-9.8)	4.6 (4.3-5.6)	1.5	0.7	0.1

Table 5.3 - Variables with non-overlap of 95% CI for signal and noise - Best$_{FTCT}$

Variable	Signal CV (95% CI)	Noise CV (95% CI)	SNR	Mean	SD
Phase: Eccentric					
Countermovement Depth [cm]	9.3 (8.4-13)	6.3 (5.8-8.1)	1.5	43.5	7.3
Eccentric Acceleration Phase Duration [s]	8.0 (7.2-11.1)	4.3 (3.9-5.5)	1.9	0.3	0.0
Eccentric Duration [ms]	7.5 (6.8-10.4)	3.0 (2.8-3.9)	2.5	481	56
Phase: Concentric					
Concentric Impulse [Ns]	6.3 (5.7-8.8)	4.2 (3.8-5.4)	1.5	270	30
Concentric Impulse 100ms [Ns]	8.4 (7.6-11.7)	5.7 (5.2-7.3)	1.5	128	21
Concentric Impulse 50ms [Ns]	9.5 (8.6-13.3)	6.6 (6.1-8.5)	1.4	71	13
Concentric Mean Power-BM [W.kg $^{-1}$]	7.3 (6.6-10.1)	5.2 (4.7-6.6)	1.4	29	4.1
Concentric Peak Force-BM [N.kg $^{-1}$]	5.1 (4.7-7.2)	3.6 (3.3-4.6)	1.4	25	2.6
Concentric RPD 50ms-BM [W.s.kg $^{-1}$]	13.8 (12.5-19.2)	9.1 (8.3-11.7)	1.5	316	86
P1 Concentric Impulse [Ns]	8.1 (7.4-11.4)	5.8 (5.3-7.4)	1.4	168	22
Velocity at Peak Power [m.s $^{-1}$]	5.9 (5.4-8.3)	4.1 (3.7-5.3)	1.4	2.5	0.3
Vertical Velocity at Takeoff [m.s $^{-1}$]	5.8 (5.2-8.1)	4.1 (3.7-5.2)	1.4	2.7	0.2
Phase: Landing					
Peak Landing Velocity [m.s $^{-1}$]	30.1 (27.3-42)	18.8 (17.2-24.2)	1.6	1.1	0.3
Phase: Composite					
Contraction Time [ms]	4.6 (4.1-6.4)	2.6 (2.3-3.3)	1.8	763	79
Peak Net Takeoff Force-BM [N.kg $^{-1}$]	10.1 (9.1-14.1)	6.9 (6.3-8.9)	1.5	16	2.8
CMJ Stiffness [N.m $^{-1}$]	12.2 (11-17)	7.1 (6.5-9.1)	1.7	6,100	1,332
Eccentric-Concentric Duration [%]	9.9 (8.9-13.8)	4.6 (4.2-5.9)	2.2	171	18
Jump Height Imp Mom [cm]	11.8 (10.7-16.5)	8.2 (7.5-10.5)	1.4	36.5	6.8
Lower Limb Stiffness [N.m $^{-1}$]	13.1 (11.8-18.2)	7.5 (6.8-9.6)	1.7	5,791	1,352

Variable	Signal CV (95% CI)	Noise CV (95% CI)	SNR	Mean	SD
Mean Eccentric Concentric Power-Time [W.s $^{-1}$]	10.8 (9.8-15)	5.9 (5.4-7.6)	1.8	2,173	350
Movement Start to Peak Power [s]	5.1 (4.6-7.1)	2.7 (2.5-3.5)	1.9	0.7	0.1
Total Work [J]	7.3 (6.6-10.2)	4.8 (4.3-6.1)	1.5	1,253	187

5.6. Discussion

The main finding of the present study was that a substantial number of CMJ variables assessed during a professional rugby season displayed week-to-week variation (i.e., signal) that is greater than the inter-day variation (i.e., noise). Indeed, most of these variables had an SNR >1.0 irrespective of whether the mean of multiple jumps or a 'best' jump of the day was selected for analysis. While this information alone does not determine how useful a variable is for monitoring athletes, an SNR ≤ 1.0 does signify that the changes observed in those variables across a season are not greater than normal methodological and biological noise and have no practical use in monitoring within the context being examined (Crowcroft et al., 2017; Ryan et al., 2019b). Of the variables with SNR >1.0, 36 had 95% CIs for signal and noise that did not overlap using at least 1 of the 3 data treatment methods. This separation between signal and noise indicates a greater probability that the responsiveness of those variables observed at team level (i.e., SNR magnitude) will also be observed at the individual level (Cumming & Finch, 2005; Wolfe & Cumming, 2004). A number of these variables have previously been identified as responsive (i.e., a large signal) (Cohen et al., 2020; Cormie et al., 2010; Hart et al., 2019; Taberner et al., 2020), results which, taken collectively, further establish their potential value in routine monitoring and in characterising responses to individual prescription and periodisation strategies.

A common technique used to reduce the number of variables for CMJ monitoring has been to disregard those that do not meet an arbitrary reliability cut-off (i.e., test/re-test CV >10%) (Claudino et al., 2017; Cormack, Newton, Mcguigan, et al., 2008a; Howarth et al., 2021). However, this approach does not account for the magnitude of changes that are observed in response to the training and competition environment (i.e., the signal) and measures with higher test/re-test variability may be useful in monitoring protocols if they display larger signal than noise. Failing to consider this in data reduction processes could lead to erroneous exclusion of these variables and consequently limit the actionable insights derived from CMJ kinetics that practitioners could gain from these assessments (Howarth et al., 2021). This concept is illustrated by data for several variables in the present study. For example, eccentric deceleration rate of force development, previously shown to be important to understanding altered CMJ kinetics in injury monitoring (Cohen, 2020; Hart et al., 2019) and across a Rugby 7's season (Lonergan, 2022) would be excluded using an inter-day reliability cut-off of CV≤10% ($Mean_3$ CV = 11.8%, $Best_{JH}$ CV = 16.7%, $Best_{FTCT}$ CV = 14.3%). . However, we determined its SNR to be >1.0 in 2 of the data treatment conditions ($Mean_3$ SNR = 1.2, $Best_{FTCT}$ SNR = 1.3), showing that typical changes through a rugby season exceed 'noise' determined in preseason. Conversely, force at peak power, a variable with excellent reliability ($Mean_3$ = 2.1%, $Best_{JH}$ = 3.4%, $Best_{FTCT}$ = 2.6%) had SNR's of ≤ 1.0 ($Mean_3$ = 0.8, $Best_{JH}$ = 0.9, $Best_{FTCT}$ = 1.0), showing that it did not respond within a rugby season. These two variables exemplify the inadequacy of depending on reliability alone to qualify a variable for use in monitoring.

Beyond using the < 1 SNR cut point and considering the SNR magnitude, by considering the magnitude of difference between signal and noise by examining the 95% CI's, practitioners can be more confident that team level SNR data apply to the individual (Cumming & Finch, 2005). In the present study, the SNR for jump height by flight-time method, a metric commonly used by practitioners and researchers (Cronin & Hansen, 2005; Kennedy & Drake, 2018), is 1.4 using the $Mean_3$ treatment and 1.2 using both the $Best_{JH}$ and $Best_{FTCT}$ treatments. While all 3 data treatment methods show the signal of this measure exceeds its noise, it is only in the $Mean_3$ method that the 95% CIs did not overlap. This approach to qualifying sensitivity, along with evidence from prior research can be helpful in evaluating variables for their use in monitoring. Three examples of this include countermovement depth and eccentric duration, which both show non-overlap of 95% CIs using all 3 data treatment methods, and concentric impulse at 100 ms, showing non-overlap in both $Mean_3$ and $Best_{FTCT}$ methods. Countermovement depth has previously been shown to decrease in response to targeted power training stimuli, along with an increase in eccentric peak power and jump height (Cormie et al., 2010), while eccentric durations (i.e., sub-phases of overall eccentric duration) are reported to decrease following extended periods away from football-specific training. Further, variables such as concentric impulse at 100 ms have been shown to be important in quantifying change in jump efficiency (Sole et al., 2018) and as benchmarks for return-to-play post anterior cruciate ligament injury (Cohen, 2020; Taberner et al., 2020). Variables that have a non-overlap of 95% CIs and a conceptual link to underlying physical qualities are, therefore, likely to provide meaningful information in routine monitoring systems (Coutts et al., 2018).

The current analyses used three different data treatment methods, showing subtle differences in the magnitude of the SNR for CMJ variables collected under the same conditions. It has previously been suggested that using the mean of multiple jumps provides greater sensitivity than examining a single jump (Claudino et al., 2017; Kennedy & Drake, 2018). For example, Mercer et al., (Mercer et al., 2021) recently reported that the SNR was larger when examining the $Mean_3$ than data from a single trial with the $Best_{JH}$ or $Best_{FTCT}$ for most variables investigated. FTCT is a commonly used variable for CMJ monitoring in team sports (Cormack et al., 2013; Gathercole, Sporer, et al., 2015a) and by using it to identify a ‘best’ jump, it selects the jump with the most efficient time-based strategy (i.e., greatest time in air achieved with the shortest contraction time). In contrast to the findings of Mercer et al (Mercer et al., 2021), the sensitivity of CMJ variables calculated using the $Best_{FTCT}$ data treatment method in our cohort was similar to those using $Mean_3$ data. Considering that there were no meaningful differences between inter-day reliability between the 'best jump' treatment methods in our cohort (Howarth et al., 2021), any differences in sensitivity between $Best_{JH}$ and $Best_{FTCT}$ must therefore be driven by differences in signal (i.e. response) throughout the season. As noted by Mercer et.al. (Mercer et al., 2021), it is likely that the differences between the two cohorts (professional rugby vs basketball athletes), such as training history, types of load exposure, test timing relative to competition (with consideration for the time course of neuromuscular fatigue) and jump protocol (arm-swing/ no arm-swing) account for the differences both in the noise and the signal values observed between these studies. Taken together, these results reinforce the assertion that practitioners should carry out their own cohort-specific analysis of measurement characteristics before finalising the selection of data treatment method for monitoring.

Overall, this work quantifies the sensitivity (i.e., SNR values) of a wide range of CMJ variables to a full season in professional rugby union players. We also highlighted variables where the 95% CIs for the signal and noise did not overlap, proposing this as a characteristic of increased confidence in identifying meaningful changes in the athlete monitoring context. Indeed, specific variables in the eccentric (e.g., countermovement depth) and early concentric phases (e.g., concentric impulse – 100 ms), previously demonstrating significant change following training and injury, were confirmed as having non-overlap of 95% CIs. While the data treatment method applied to a series of jumps only mildly affected sensitivity, $Mean_3$ data treatment yielded the greatest number of variables with an SNR > 1.0. Further, the sensitivity of $Best_{FTCT}$ measures were similar to those of $Mean_3$ and with higher sensitivity of a greater number of variables than $Best_{JH}$, making it a better criterion to select a 'best' jump for analysis. These results should be interpreted with consideration to the influence of the timing of an assessment relative to load exposure of the athletes on neuromuscular status and the differing time course of recovery of CMJ variables following high intensity exercise (Gathercole, Sporer, et al., 2015a), and it cannot be assumed that results obtained in this Thursday scenario can be used interchangeably with a Monday or match-day +2 assessment.

Practitioners are faced with time constraints when processing and interpreting load and load-response data obtained in competition and training, therefore there is a need for simple, reductionist approaches to inform decision making. We also advocate that "more things should not be used than are necessary" (Coutts, 2014) and the need to achieve a more parsimonious variable group for monitoring. The approach described can assist in CMJ data reduction using a statistical approach that integrates both signal and noise information and uses cohort and monitoring condition-specific data to assist in the selection of appropriate variables in the context of where they are being applied. This approach may also help prevent the erroneous exclusion of variables for individual monitoring. Combining SNR information with other data reduction approaches (e.g., principal component analysis) (James et al., 2021) and practitioner expertise (Coutts, 2017), provides an evidence-based framework for choosing CMJ variables that are valuable in the athlete monitoring process.

5.7. Practical applications

Along with validity and reliability, sensitivity is an important measurement characteristic for practitioners to be aware of when considering which variables to include in monitoring protocols that inform practice. A potential screening for high level inclusion is to utilise the data treatment that yields the greatest number of sensitive variables, then select the variables with non-overlap of 95% CIs for signal and noise for consistent monitoring. However, while 'less sensitive' variables may not form part of regular monitoring processes at a team level, they may be important on an individual level as a large change may indicate a meaningful response - a concept that is not unique to CMJ analysis. If multiple jumps are performed as part of monitoring assessments, the choice of data treatment - use of mean versus a best jump should also be considered, as differences in sensitivity are evident. Given the differences in results between cohorts and protocols, we regard our findings as relevant to this group of professional rugby players who are monitored under the conditions described. We emphasise that practitioners should carry out a sensitivity analysis using a combination of inter-day reliability and monitoring data collected in their cohort to identify the most sensitive variables and data treatment method. However, during the process of gathering a season's signal data, or if inter-day reliability data was not obtained, the present analysis may provide some guidance on variable sensitivity.

Chapter 6

Study 3:

Reducing the noise: an agnostic approach to data reduction for monitoring changes in countermovement jump kinetic variables.

Howarth, D. J., McLean, B. D., Cohen, D. D., & Coutts, A. J. Removing the noise: An agnostic approach to data reduction for monitoring changes in countermovement jump kinetic variables.

6.1. Preface

Combining the results of Chapter 4 and Chapter 5, the most sensitive CMJ variables have been identified for this cohort of rugby union players. In this chapter we explore the variable data-set for redundancies by analysing the co-variance of each CMJ variable. This explores step 3 of the framework detailed in Chapter 3.

6.2. Abstract

Variables calculated from countermovement jumps (CMJs) on force plates are often used to monitor athletes' responses to training and competition. Currently, force plate software processes raw force-time data in real time, rapidly calculating large numbers of CMJ variables. This can provide a wealth of insights in athlete NM status but may also create data management issues, making appropriate means to identify the most relevant variables important. Principal component analysis (PCA) is a statistical method that can be employed in this process. A PCA can transform an extensive list of variables into smaller groups of highly correlated variables, known as principal components. This retains most of the original information but reduces the dimensionality of the data making it easier to interpret and analyse. We used a PCA on CMJ variables (n = 74) collected in 36 professional rugby players in a pre-season assessment. Variables were separated into 4 phase groupings prior to analysis: 'eccentric' (downward) (n = 21), 'concentric' (upward) (n = 20), landing (n = 10), and a 'composite' measure category (n = 23). Each grouping was tested for adequate correlation between measures (Bartlett's test of sphericity) and for sampling adequacy (Kaiser-Meyer-Olkin measure). PCAs were then performed on each different dataset using oblique rotation (promax), with component selection based on an eigenvalue >1.0. A factor load ≥ 0.6 was applied to the variable results for inclusion in principal components. We found that PCA isolated 2-5 principal components within each of the four CMJ variable groups (eccentric, concentric, landing, and composite), which

collectively account for 80-98% of the variability in each group's result. Identification of multiple components within each phase of the CMJ suggests that practitioners should retain a range of variables and/or groupings for each CMJ phase, making PCA an effective process to aid in the reduction of CMJ variables.

6.3. Introduction

Variables derived from vertical ground reaction forces collected by force platforms during countermovement jumps (CMJs) are commonly used to characterise responses to training and competition (Cohen, 2020; Cormack, Newton, McGuigan, & Cormie, 2008; Cormie et al., 2009b) This helps practitioners to quantify training adaptation (Cronin & Hansen, 2005; McMaster et al., 2014) fatigue (Bishop et al., 2023; Claudino et al., 2017; Cohen, 2020), and inform injury rehabilitation (Cohen, 2020; Hart et al., 2019). Software accompanying contemporary force platforms process ground reaction forces in real time, instantaneously calculating >100 variables from each CMJ (Bishop et al., 2021; Claudino et al., 2017). However, the increased accessibility to a vast list of variables may overwhelm practitioners and impede their ability to effectively interpret test data in a timely and effective manner (Merrigan et al., 2022). To aid in timely interpretation of data, variable reduction processes have involved arbitrary inclusion or exclusion of variables and information loss (Bishop et al., 2023; Bishop et al., 2021). Therefore, a systematic approach with appropriate methods is required to identify the most useful variables (Coutts, 2014), including quantification of the measurement characteristics of a given variable (e.g., validity, reliability, sensitivity).

Statistical methods that explore the data for commonalities can be employed to help facilitate practitioners in making informed decisions during the creation of more parsimonious approaches to understanding changes in CMJ variables. Principal Component Analysis (PCA) is one such method and is particularly useful for exploring high-dimensional data sets like variables derived from CMJ. While detailed ground reaction force-time continuous waveforms generated from CMJ can be analysed (Richter et al., 2014a, 2014b), it is more common for practitioners to utilise summary variables, such as peak forces, rates of force development, jump height, and peak power (Cormack, Newton, Mcguigan, et al., 2008a; Cormie et al., 2009b; Gathercole, Sporer, et al., 2015a; Heishman et al., 2018; Howarth et al., 2021), which may obfuscate the meaningful patterns within the data. PCA transforms the original list of variables into a new set of variables, known as principal components, which are orthogonal (uncorrelated), and which reflect the maximum variance within the data (Jolliffe & Cadima, 2016). Within the PCA, the first principal component reflects the most variance, the second (which is orthogonal to the first) reflects the second most, and so on (Abdi & Williams, 2010). This analysis the dimensionality of the data is reduced while retaining most of the original variability, making it easier to interpret and analyse (Abdi & Williams, 2010; Matsunaga, 2010).

The variables within each principal component are linked by their covariance, in that each variable within a group will tend to vary together in a specific way. Co-variance serves as the mathematical backbone that enables PCA to cluster correlated variables together into a singular component (Abdi & Williams, 2010). For example, in a PCA applied to CMJ variables, if a component were to comprise variables such as jump height, peak power, and take-off velocity, the findings suggest there is a close relationship among these variables and that they convey similar information about the test. Prior research applying PCA to 27 CMJ variables in collegiate American Football players (Merrigan, Stone, et al., 2021) and 16 CMJ variables in elite junior Australian Football players (James et al., 2021) demonstrates that more than 90%

of the total variance in each dataset is captured in 3 or 4 components. Longitudinal tracking of multiple measures from the same component could therefore indicate redundancy.

When conducting PCA, several statistical assumptions must be met to ensure robust and interpretable results. Firstly, variables should be measured on an interval scale and exhibit linear relationships with some degree of correlation, while also demonstrating multivariate normality to enhance generalisability of findings (Jolliffe & Cadima, 2016). Additionally, there is a requirement to have more subjects than the number of variables being analysed (Abdi & Williams, 2010; Matsunaga, 2010). Previous research has reduced variables by using a priori criteria, such as pre-selecting only those variables that have been commonly researched (James et al., 2021), using variables that, based on subjective assumptions, will improve model validity (Merrigan, Rentz, et al., 2021), or have sufficient reliability (e.g., CV ≤10%) (Anicic et al., 2023). Each of these 'guided' approaches, involving the pre-selection of a variable subset, is problematic due to their reliance on arbitrary inclusion criteria. To overcome this limitation, an initial step of simplifying the variable pool to align with the primary focus of the investigation (e.g., only analysing bilateral variables when measuring neuromuscular fatigue by removing asymmetries and single leg values) (Howarth et al., 2021) will effectively reduce the number of variables. A further practical solution is to separate CMJ variables into phase groupings (i.e., eccentric/downward, concentric/upward, landing). This method enables performing separate PCAs on these smaller groups of variables (that is, fewer variables in each PCA compared to the number of players), while still including all available variables in the analysis.

To address the lack of research investigating an inclusive list of CMJ variables with PCA, this study aims to implement a comprehensive exploration of CMJ variable covariance, using phase grouped variables from assessments of professional rugby union players.

6.4. Methods

6.4.1. Experimental approach to the problem

A cross-sectional research design was used to explore a wide range of bilateral CMJ variables (n = 74) collected in assessments of professional rugby players. The assessments analysed were performed during preseason testing. Reliability of these same variables was reported previously (Howarth et al., 2021). In order to satisfy the requirement of more subjects than variables and in line with the suggestion that phase-by-phase analysis may enhance the diagnostic potential of kinetic information from the CMJ (Sole et al., 2018), variables were separated into groups by the phase of the jump in which they occurred; eccentric (downward), concentric (upward), and landing phases. All other variables did not fit within one of these phases was therefore termed a 'composite' variable, forming a fourth group. Four separate PCAs were then performed, one on each group of variables, to determine groups of highly correlated variables (i.e., principal components). Descriptions for the calculation of each variable are available in Appendix 1 of the supplementary material. These procedures were repeated in data collected under similar conditions at two time points separated by 7 days (i.e., consecutive Mondays) at the beginning of pre-season. This was done to determine if components would consistently form within the CMJ data in this group.

6.4.2. Subjects

Forty-three rugby union players who competed in Pro 14 and European Challenge Cup competitions were included in this study. From this initial group, 3 players were not present during the testing period due to commitments with the National Team and 4 were omitted from regular CMJ tests due to injury. The final cohort consisted of 36 male professional rugby union players (mean ± SD; age 24 ± 5 years, height 184.8 ± 8.1 cm, body mass 102.8 ± 11.9 kg). All participants provided their informed written consent to participate in this study, which was approved by the Human Research Ethics Committee at the University of Technology Sydney (ETH19-3614).

6.4.3. Procedures

Before testing, the following standardised warm-up was completed twice: (i) self-selected soft tissue and mobility treatment; (ii) 5 band resisted overhead squats; (iii) 5 band resisted Romanian deadlifts; (iv) 3 band resisted broad jumps; (v) 10 pogo jumps and (vi) 10 m of A-Skips. A 25 mm power band (BLK Box, Belfast, Northern Ireland) was used as resistance for the 'band resistance' exercises. Each player completed the CMJ test within 2-3 minutes after finishing the warm-up.

The CMJs were performed on a dual force plate system (NMP ForceDecks FD-4000–Vald Performance, Brisbane, Australia) as described elsewhere (Howarth et al., 2021). After completion of 3 repetitions, the analysis of the CMJ force-time curves was completed using ForceDecks software (v2.0.7418, Vald Performance, Brisbane, Australia). Every CMJ was visually monitored for appropriate technique by an experienced member of the staff. Any jumps deviating from the standard protocol (e.g., jumpers attempted to 'tuck' their legs during the flight phase, double jump/pre-jump, did not land on the force plates) were excluded and another jump was performed to ensure 3 acceptable trials.

6.4.4. Statistical analyses

According to our previous research (Howarth et al., 2021; Howarth et al., 2023), of the 104 bilateral kinetic variables calculated from the CMJ, 19 were excluded as they were meta-data used in the calculation of other metrics, and a further 11 were excluded in preference for their body-mass relative equivalent. The remaining 74 variables were prepared for analysis by calculating the mean for each value in 3 jump trials ($Mean_3$) as this method has been shown in several studies to produce reliable and sensitive results for the CMJ variables (Claudino et al., 2017; Howarth et al., 2021; Howarth et al., 2023; Kennedy & Drake, 2018). All data were log-transformed to bring results onto the same scale thus reducing any unit of measurement bias. To achieve the requirement of having more subjects than variables in each PCA, results were separated into 4 phase groupings of variables prior to analysis: eccentric phase ($n = 21$, concentric phase ($n = 20$), landing phase ($n = 10$), and 'composite' measures ($n = 23$). Each grouping was tested for adequate correlation between measures (Bartlett's test of sphericity) and for sampling adequacy (Kaiser-Meyer-Olkin measure) (James et al., 2021; Ryan et al., 2019b). The PCAs were then performed on the eight different datasets using oblique rotation (promax) and component selection based on an eigenvalue >1.0, as suggested in previous research (Matsunaga, 2010; Ryan et al., 2021). To reduce redundancies, a factor load ≥ 0.6 (i.e., conservative level of correlation between variable and component) was applied to the variable results for inclusion in principal components (Matsunaga, 2010). All analyses and transformations were performed in Jamovi statistical software (Version 2.3.21, The Jamovi Project, Sydney, Australia).

6.5. Results

Between variable correlation, evaluated using Bartlett's test of sphericity, was significant ($p \leq 0.05$) for each of the phase groups for the data on both days the PCA was performed (**Table 6.1**). The Kaiser Meyer-Olkin measures show that each data set reached an acceptable level of sampling adequacy (MSA ≥0.50) for each of the phase groups on both days. These collective results indicate that each data set was appropriate for PCA.

In the eccentric phase (**Table 6.2**), 5 components were identified with an eigenvalue >1, explaining 96.4% of the total variance in the results on $Monday_1$ and 96.7% on $Monday_2$. For the concentric phase (**Table 6.3**), four components were identified, which explain 98.3% ($Monday_1$) and 98.7% ($Monday_2$) of total variance in the results. The first principal component consisted primarily of time-limited variables. Two components in the landing phase were identified (**Table 6.4**), explaining 82.8% ($Monday_1$) and 80.2% ($Monday_2$) of total variance. From the grouping of composite variables, 5 components were identified (**Table 6.5**), explaining 91.1% ($Monday_1$) and 93.2% ($Monday_2$).

Four of the 74 variables examined did not load consistently to a component on both days: minimum eccentric force (**Table 6.2**), take-off peak force (**Table 6.5**) peak net take-off force (**Table 6.5**) and reactive strength index modified (**Table 6.5**).

Table 6.1 - Measures examining adequacy of correlation.

$Monday_1$	χ^2	**df**	**p**	**MSA**
Eccentric Variables	2149.50	190	< .001	0.66
Concentric Variables	2634.34	171	< .001	0.60
Landing Variables	743.83	55	< .001	0.58
Composite Variables	2812.21	276	< .001	0.67
$Monday_2$	χ^2	**df**	**p**	**MSA**
Eccentric Variables	2013.63	190	< .001	0.60
Concentric Variables	2364.76	171	< .001	0.71
Landing Variables	650.97	55	< .001	0.58
Composite Variables	2527.64	276	< .001	0.65

Between measures (Bartlett's Test of Sphericity) and sample (Keyser-Meyer-Olkin Measure of Sampling Adequacy) for both days of testing ($Monday_1$ and $Monday_2$). χ^2 = chi-squared value; df = degrees of freedom in the dataset; p = significance of correlation in dataset from Bartlett's Test of Sphericity (significance set at $p \leq 0.05$); MSA = Measure of Sampling Adequacy from Keiser-Meyer-Olkin (adequacy interpreted as MSA $\geq$ 0.50)

Table 6.2 - Component groups and unique variables as identified by PCA for eccentric phase variables.

Components	*Factor Loading Monday$_1$*	*Factor Loading Monday$_2$*
Component 1	*(46.62% of variance, eigenvalue: 9.32)*	*(45.33% of variance, eigenvalue: 9.07)*
Eccentric Deceleration RFD [N/s/kg]	1.06	1.09
Eccentric Deceleration Phase Duration [s]	-1.01	-0.99
Eccentric Peak Force [N]	1.00	1.06
Eccentric Braking RFD [N/s/kg]	0.87	0.89
Braking Phase Duration [s]	-0.83	-0.79
Component 2	*(18.89% of variance, eigenvalue: 3.78)*	*(17.55% of variance, eigenvalue: 3.51)*
Eccentric Mean Braking Force [N]	1.07	1.00
Eccentric Mean Deceleration Force [N]	0.81	0.82
Force at Zero Velocity [N]	0.79	0.72
Eccentric Deceleration Impulse [Ns]	0.79	0.92
Eccentric Unloading Impulse [Ns]	0.78	0.92
Eccentric Braking Impulse [Ns]	0.74	0.65
Component 3	*(15.64% of variance, eigenvalue: 3.13)*	*(16.94% of variance, eigenvalue: 3.39)*
Eccentric Peak Velocity [m/s]	0.95	0.90
Eccentric Mean Power [W/kg]	0.85	0.94
Eccentric Peak Power [W/kg]	0.76	0.65
Countermovement Depth [cm]	0.71	0.77
*****Minimum Eccentric Force [N]***	***NA***	***-0.56***
Component 4	*(8.92% of variance, eigenvalue: 1.78)*	*(9.59% of variance, eigenvalue: 1.92)*
Time to Braking Phase [s]	1.05	1.02
Eccentric Acceleration Phase Duration [s]	0.94	0.98
Eccentric Duration [ms]	0.71	0.68
*****Minimum Eccentric Force [N]***	***0.59***	***NA***
Component 5	*(6.29% of variance, eigenvalue: 1.26)*	*(7.30% of variance, eigenvalue: 1.46)*
Eccentric Braking RFD – 100ms [N/s/kg]	0.94	-1.01

RFD = rate of force development, RPD = rate of power development, ** = not loaded consistently one component

Table 6.3 – Component groups and unique variables as identified by PCA for concentric phase variables.

Components	***Factor Loading Monday$_1$***	***Factor Loading Monday$_2$***
Component 1	*(47.57% of variance, eigenvalue: 9.04)*	*(54.73% of variance, eigenvalue: 10.40)*
P2 Con Impulse/P1 Con Impulse Ratio	-1.00	-1.03
Concentric RPD – 50ms [W/s/kg]	0.86	0.80
Concentric Peak Force [N/kg]	0.86	0.80
Con Impulse 100ms/Con Impulse Ratio	0.79	0.87
Concentric Impulse – 50ms [Ns]	0.77	0.80
Concentric Impulse - 100ms [Ns]	0.64	0.68
Concentric RPD – 100ms [W/s/kg]	0.61	0.62
Component 2	*(30.00% of variance, eigenvalue: 5.70)*	*(25.00% of variance, eigenvalue: 4.75)*
Velocity at Peak Power [m/s]	1.07	1.07
Vertical Velocity at Takeoff [m/s]	1.02	1.03
Concentric Peak Velocity [m/s]	1.02	1.02
Concentric Peak Power [W/kg]	0.81	0.87
Concentric Mean Power [W/kg]	0.78	0.77
Component 3	*(13.79% of variance, eigenvalue: 2.62)*	*(13.11% of variance, eigenvalue: 2.49)*
Force at Peak Power [N]	1.02	0.95
Concentric Impulse [Ns]	0.91	0.93
P1 Concentric Impulse [Ns]	0.80	0.80
P2 Concentric Impulse [Ns]	0.62	0.60
Component 4	*(6.96% of variance, eigenvalue: 1.32)*	*(5.82% of variance, eigenvalue: 1.11)*
Concentric RPD [W/s/kg]	0.92	0.84
Concentric Duration [ms]	-0.91	-0.86
Concentric Mean Force [N/kg]	0.79	0.67

RFD = rate of force development, RPD = rate of power development, ** = not loaded consistently one component

Table 6.4 - Component groups and unique variables as identified by PCA for landing phase variables.

Components	***Factor Loading Monday$_1$***	***Factor Loading Monday$_2$***
Component 1	*(54.73% of variance, eigenvalue: 8.91)*	*(56.03% of variance, eigenvalue: 6.16)*
Landing Net Peak Force [N/kg]	0.95	0.95
Peak Landing Force [N/kg]	0.95	0.95
Jump Height Relative Landing RFD [N/s/cm]	0.90	0.89
Peak Landing Power [W]	0.89	0.89
Landing RFD [N/s]	0.89	0.88
Jump Height Relative Peak Landing Force [N/cm]	0.77	0.80
Component 2	*(28.11% of variance, eigenvalue: 4.95)*	*(24.14% of variance, eigenvalue: 2.66)*
Peak Landing Velocity [m/s]	-0.86	-0.79
Landing Impulse [Ns]	0.78	0.83
Mean Landing Power [W]	-0.77	-0.68
Landing RFD – 50ms [N/s]	0.68	0.62

RFD = rate of force development, RPD = rate of power development, ** = not loaded consistently one component

Table 6.5 - Component groups and unique variables as identified by PCA for composite variables.

Components	*Factor Loading Monday$_1$*	*Factor Loading Monday$_2$*
Component 1	*(43.80% of variance, eigenvalue: 10.51)*	*(42.22% of variance, eigenvalue: 10.13)*
Contraction Time [ms]	-0.94	-1.02
Movement Start to Peak Power [s]	-0.94	-1.03
Lower Limb Stiffness [N/m]	0.91	0.92
Flight Time/Contraction Time Ratio	0.89	0.85
Eccentric/Concentric Mean Force Ratio	-0.88	-0.74
CMJ Stiffness [N/m]	0.87	0.88
Mean Ecc + Mean Con Power/Time [W/s]	0.81	0.92
*****Takeoff Peak Force [N/kg]***	*0.78*	***NA***
*****Peak Net Takeoff Force [N/kg]***	***0.78***	***NA***
Movement Start to Peak Force [s]	-0.73	-0.81
*****Reactive Strength Index Modified***	***0.71***	***NA***
Component 2	*(20.62% of variance, eigenvalue: 4.95)*	*(21.80% of variance, eigenvalue: 5.23)*
Flight Time [ms]	0.97	1.00
Jump Height – Flight Time [cm]	0.97	1.00
Jump Height – Impulse/Momentum [cm]	0.82	0.88
*****Reactive Strength Index Modified***	***0.62***	***0.73***
Component 3	*(10.11% of variance, eigenvalue: 2.43)*	*(11.18% of variance, eigenvalue: 2.68)*
Contraction Time/Eccentric Duration Ratio	0.96	0.96
Eccentric/Concentric Duration Ratio	-0.95	-0.96
Ecc Peak Power/Con Peak Power Ratio	0.62	0.69
Component 4	*(9.81% of variance, eigenvalue: 2.35)*	*(7.57% of variance, eigenvalue: 1.82)*
Positive Takeoff Impulse [Ns]	0.94	0.92
Total Work [J]	0.90	0.86
Positive Impulse [Ns]	0.70	0.75
Component 5	*(6.72% of variance, eigenvalue: 1.61)*	*(9.83% of variance, eigenvalue: 2.36)*
Braking Phase Duration/Contraction Time Ratio	0.92	1.02
Braking Phase Duration/Concentric Duration Ratio	0.84	0.91

RFD = rate of force development, RPD = rate of power development, ** = not loaded consistently one component

6.6. Discussion

The main finding of this study was that the PCA isolated 2-5 principal components within each of the four CMJ variable groups (eccentric, concentric, landing, and composite), which collectively account for 80-98% of the variability in each group's result. Identification of multiple components within each phase of the CMJ suggests that practitioners should retain 2-5 variables and/or groupings for longitudinal monitoring of each CMJ phase. In doing so, data redundancy is reduced (e.g. monitoring less than 74 variables) while still retaining enough information to identify changes in the specific aspects of jump strategy represented by each component (James et al., 2021; Sole et al., 2018). This approach can be used to streamline CMJ monitoring, reducing the number of variables to a manageable level without sacrificing the critical insights each component offers into specific jump strategies.

The present study advances previous research that has used PCA to CMJ data by exploring a larger number of discrete variables (i.e., 74 vs. 28 variables). To achieve this without violating statistical assumptions, we examined the CMJ data in a phase-by-phase manner, a method not previously employed. In the current data set, we identified 5 components in the eccentric phase, 4 in the concentric phase, 2 in the landing phase, and 5 in the composite grouping. For practical application, three methods have been suggested to be suitable for representing each dimension for ongoing athlete monitoring: i) creating a single composite metric using the change scores from all variables in each component (James et al., 2021); ii) identifying and using the most strongly loaded variable in each component (Abdi & Williams, 2010); or (iii) selecting a single 'representative' variable from each component based on other measurement characteristics (e.g., sensitivity) (Matsunaga, 2010). By utilising PCA to understand co-variance, this research reveals that for this particular cohort, it was possible to reduce the number of bilateral variables used to monitor CMJs from 74 to 16, while still retaining much of the potential diagnostic quality that has been espoused by previous research (Cohen, 2020; Gathercole, Sporer, et al., 2015a; Sole et al., 2018). Indeed, should the practitioner choose to retain the most sensitive variable from each component (as suggested in Option iii above), they can be more confident that monitoring variables are responsive to training stimuli and therefore suited to longitudinal athlete monitoring (Howarth et al., 2023).

The PCA revealed clusters of CMJ variables that account for the majority of variance across various dimensions, primarily through the rotation of variable correlation analyses (Merrigan, Rentz, et al., 2021). This approach often leads to the discovery of common traits among many CMJ variables in a component, which play a pivotal role in determining its structure (Anicic et al., 2023; James et al., 2021; Merrigan, Rentz, et al., 2021). For example, Component 3 in the eccentric phase PCA was made up of variables that are all calculated via numerical integration. However, PCA is not designed to examine underlying constructs of each component, but rather to highlight where metrics co-vary, indicating the likely redundancy when analysing changes in multiple variables from a single component (Matsunaga, 2010). Even so, components are numerically ordered based on the amount of variance they explain across each of the dimensions examined (Matsunaga, 2010), providing insight to which groups of variables have a greater impact on the total variance within the data set. For example, many variables comprising the first principal component in the eccentric and concentric phases are calculated over a specific time interval or within a defined "sub-phase". Such variables include concentric rate of power development at 50 ms and eccentric deceleration duration – other examples and further details on these variable calculations can be found in Appendix 10. These components explain between 45- 55% of the variance in these data sets. Prior research has highlighted how this kind of information aids in understanding both positional and individual differences in CMJ kinetics (Merrigan, Rentz, et al., 2021), which can provide important context for data interpretation and subsequent interventions (i.e., training or recovery activities) implemented by the practitioner.

In addition to identifying variables that exhibit a large amount of shared variance, PCA also highlights variables that do not load consistently to any single component. Such variables are considered 'random' when they load to several components (Matsunaga, 2010) or ‘unique’ when they do not load to any components (Ryan et al., 2021). Our results highlight 4 variables that do not load to the same components consistently between both days of data collection: minimum eccentric force, take-off peak force, peak net take-off force, and reactive strength index modified. This observed randomness in component loading suggests that these variables do not measure a consistent construct over time for this group. Consequently, variables that demonstrate this randomness should be considered for removal from further analysis as they do not reliably represent the underlying construct. In our results, eccentric braking RFD - 100 ms emerged as the sole variable to be classified as unique. It consistently forms its own component (**Table 5.2**) and meets critical criteria with a loading factor ≥ 0.6, indicating that it is strongly correlated with the component structure, and eigenvalue ≥ 1, showing that it is impactful as a component on the overall variance in jump results (Ryan et al., 2021). Rather than omission from further use, these results suggest that eccentric braking RFD – 100 ms could be an important variable to retain in this group, if it is responsive to changes in athlete status throughout a season (Howarth et al., 2023).

Observed measurement characteristics and principal components vary between groups of athletes, meaning that cohort specific analyses are practically important for practitioners using force platforms to analyse CMJ data (Cohen et al., 2020; Taberner et al., 2020). However, the constraints of PCA, specifically the ratio of subjects to variables, pose challenges for analysing data co-variance in small teams (e.g., basketball vs rugby). In these scenarios, practitioners might consider adopting methodology similar to what we have explored here, by chunking CMJ variables into smaller time-based groups. In cases involving extremely small groups or single athletes, monitoring a broader selection of CMJ variables may be practical, as the need for quick data processing is less critical. The resources at a practitioner's disposal, including time and analytical capabilities, also play a crucial role in the feasibility of in-depth data collection and analysis. As a result, performing detailed, cohort-specific analysis might not always be practical. Alternative approaches involve synthesising with similar research to create an informed variable selection process (e.g., retain only variables passing a measurement characteristic criterion such as signal to noise ratio >2) (Mercer et al., 2022). However, we caution against the use of arbitrary cut-offs, considering the previously mentioned limitations of these approaches. Instead, it would be more prudent to consider the results of this study as a preliminary guide, until a coordinated effort with other practitioners can be made to ensure a larger group of subjects could be analysed.

By analysing CMJ data using PCA and integrating this with an understanding of measurement characteristics, practitioners can objectively and agnostically ensure that the variables retained are statistically important. The results of this process, specifically the variables chosen for assessing CMJ changes, can subsequently be utilised to quantify the response of the neuromuscular system to in both the short-term (e.g., single training session and game loads) (Gathercole, Sporer, et al., 2015a) and long-term (e.g., phase or season-long training program) (Mercer et al., 2022).

6.7. Practical applications

To reduce the dimensionality of CMJ variables, practitioners should consider using PCA with data collected from their specific athlete cohort. When employing PCA, phase-by-phase approach is suggested to examine all available variables and to retain the diagnostic benefits of phase-specific investigations (Sole et al., 2018). After determining the components via PCA, selecting the most sensitive variable from each component can provide a concise and effective list for use in athlete monitoring. By applying the approaches detailed in this study, practitioners can effectively reduce their variable pool while maintaining a focus on those variables most responsive to training and game adaptations. Further investigation can then be conducted that examines the effects of different types of training load on these variables or, indeed, the effect of change in these variables on performance.

Chapter 7

Study 4:

Neuromuscular response to training load in professional rugby union players

Howarth, D. J., McLean, B. D., Cohen, D. D., & Coutts, A. J. Neuromuscular response to training load in professional rugby union players

7.1. Preface

This chapter now utilizes the combined knowledge of measurement characteristics found in Chapter 4, Chapter 5, and Chapter 6 and utilizes step 4 of the framework detailed in Chapter 3. The variables that emerged as the most sensitive representatives of each major component can now be investigated for their sensitivity to training loads throughout a competitive season.

7.2. Abstract

Objective: This study investigated the effects of cumulative training and game training loads on neuromuscular function in professional rugby union players, aiming to elucidate the dose-response relationship between training loads and neuromuscular status.

Methods: We employed a retrospective descriptive observational design, analysing data collected from 28 professional male rugby union players throughout one season in the Pro14 and Challenge Cup competitions. Neuromuscular function was assessed using select countermovement jump (CMJ) metrics, while training loads were quantified using global positioning systems (GPS) for running metrics, volume load for resistance training, and session rate of perceived exertion (sRPE). Linear mixed-effects models were utilised to examine the associations between cumulative training loads and changes in CMJ variables.

Results: A total of 1,287 CMJ tests were analysed. Significant associations were observed between training loads and neuromuscular responses. On Mondays, the 3-day total distance negatively affected the concentric CMJ variables, while chronic (28-day) resistance training loads influenced the eccentric and concentric CMJ metrics. On the contrary, the CMJ tests on Thursday showed significant effects of the 7-day total load of sRPE, with positional demands influencing the variability. 28-day total distance (TD) and very high-speed running (VHSR) had opposing effects on CMJ variables.

Conclusions: Collectively, these results demonstrate the nuanced nature by which the neuromuscular system responds to 3, 7, and 28- day cumulative training loads. In particular, these findings also highlight the value of utilising different testing constructs (i.e., Monday and Thursday testing) for countermovement jumps to better understand neuromuscular response to load based on the temporal proximity to training and matches.

7.3. Introduction

Professional rugby union players are subjected to diverse physical demands throughout a season (Austin et al., 2011; Quarrie et al., 2013; Roberts et al., 2008) that may yield both adaptive (e.g., enhanced fitness, strength, and power) (Lonergan, 2022; Roe, Darrall-Jones, et al., 2016; Troester & Duffield, 2019; Troester et al., 2019) or detrimental outcomes (e.g., fatigue, soreness, and injury risk) (Davidow et al., 2020; Hulin et al., 2016; Lacome et al., 2017). Changes to the neuromuscular system - the intricate network of neural and muscular components that orchestrates voluntary and reflexive movements (Aagaard, 2003; Enoka & Duchateau, 2008) - impact performance outcomes in athletes (Nicol et al., 2006). Specifically, acute neuromuscular fatigue has been shown to impair key performance metrics like sprinting efficiency, maximum speed, and power (Edwards et al., 2018b; Gabbett, 2008), while chronic adaptation to repeated, stressful stimuli to the neuromuscular system has been linked to reduced injury incidence and enhanced athletic performance (Roe, Darrall-Jones, et al., 2016). Over time, however, athletes who do not adapt to training because of inadequate recovery or inappropriate training stimulus can accumulate neuromuscular fatigue, which could decrease their ability to perform (Davidow et al., 2020; Enoka & Duchateau, 2016). This underscores the necessity of monitoring training loads and their neuromuscular repercussions (Jeffries et al., 2021) to inform training prescription that extends beyond traditional periodisation strategies (Kiely, 2012).

Due to the multifaceted needs of a team sport season, practitioners should incorporate tools that aim to measure fluctuations of fitness and fatigue in a well-constructed conceptual framework that quantifies training load and training effect, to understand their effects on performance outcomes (Jeffries et al., 2021). The countermovement jump (CMJ) can be used to quantify neuromuscular function as a training effect (Jeffries et al., 2021), with jump height correlating to rugby-specific tasks such as sprinting and agility (Cronin & Hansen, 2005) and ground reaction force variables reflecting seasonal neuromuscular variations (Howarth et al., 2021; Howarth et al., 2023). The non-fatiguing nature of the CMJ test permits frequent data collection within typical athletic training regimens, facilitating the analysis of neuromuscular responses to training, which can then be used to inform training programming decisions for individual athletes (Howarth et al., 2021; Howarth et al., 2023). This can be achieved by linking the changes in neuromuscular function to the training loads quantified (Jeffries et al., 2021).

There are many proxy measures of the constructs of training load (Impellizzeri et al., 2023). In rugby union, these measures include data from global positioning systems (GPS) for running distances and intensities (Cunniffe et al., 2009), volume and intensity metrics for resistance training (Tavares et al., 2017), and session-RPE (Jones, Griffiths, et al., 2017). Different stimulus provided by the various training and game loads could elicit changes in neuromuscular status with varying temporal effects; for instance, a high volume of resistance training may elicit a different response acutely than the same volume applied over a longer period. The link between training load and the acute neuromuscular fatigue assessed via CMJ has been described in other sports like Australian rules football (Cormack, Newton, McGuigan, & Cormie, 2008) and rugby league (Naughton et al., 2021; Twist & Highton, 2013). However, the specifics of neuromuscular responses to varied training load prescriptions has yet not been examined. Therefore, this study aims to elucidate the effects of cumulative training and game loads on neuromuscular function in professional rugby union players, broadening our understanding of these variable effects.

7.4. Methods

7.4.1. Experimental approach to the problem

This study employed an exploratory research design, using data collected from one team over the course of one season in the Pro14 and Challenge Cup rugby competitions in Europe (June – May). As part of regular monitoring practices, the team collected CMJ data (ForceDecks v2.0.7418, Vald Performance, Brisbane, Australia), on-field running training load (GPS tracking StatSports Sonra v 3.0.08291, Belfast, Northern Ireland, UK), resistance training volume load – the product of weight lifted and reps completed (Campbell et al., 2017) of all primary exercises in lower-body focused gym sessions, and internal training load using the session rate of perceived exertion (sRPE) x duration method (Foster et al., 2001).

7.4.2. Subjects

The original testing cohort consisted of 43 professional male rugby union players who competed in the Pro14 and Challenge Cup competitions. Data from 15 players were excluded because they did not complete a predetermined threshold of a minimum of 20 CMJ testing sessions in the season between Monday and Thursday combined. All healthy players participated in training and testing, meaning that missed training or testing sessions were only due to injury, illness, or absence from the training environment (e.g., national team assignment). The final analysis consisted of 28 players (mean ± SD; age 24 ± 4 years [range 19-33], height 183.7 ± 7.8 cm, body mass 101.4 ± 10.2 kg). All players provided written informed consent and volunteered to participate in this study. The study was approved by the Human Research Ethics Committee at the University of Technology Sydney (ETH19-3614).

7.4.3. Procedures

7.4.3.1. External training load

External training load data was collected for each player from all on-field and lower-body resistance training activities. During on-field activities (i.e.., team technical and tactical trainings sessions, unit group training sessions, fitness training and games) players wore a GPS player tracking system sampling at 50 Hz (StatSports Sonra, Belfast, Northern Ireland, UK). The unit was worn between the scapulae in a customised pouch attached to each players' training and game jerseys. After all activities, data was downloaded using proprietary software (StatSports Sonra v 3.0.08291, Belfast, Northern Ireland, UK). When units malfunctioned or failed to collect data, loads were estimated by multiplying the session active duration (sum of individual drill times minus rest breaks) by that individual's minute average workloads for that given type of activity (e.g., game load, warm-up, skill rotations, 15 vs. 15 practice). There were 6 occasions where data were estimated and calculated in this way throughout the duration of the study. Total distance (TD) and relative very-high speed running (VHSR) (i.e., distance travelled above speeds >70% of individual maximum velocity) were selected for use in subsequent analysis, as these variables have been shown to differentiate the physical demands of position (Cunniffe et al., 2009; Lacome et al., 2014; Lacome et al., 2017) and competition level (Austin et al., 2011; Quarrie et al., 2013; Roberts et al., 2008) in rugby union. To determine the external load from resistance training, players reported the weights achieved in their primary lower-body sessions to a practitioner, who then collated them in a customised excel spreadsheets (Microsoft, Redmond, WA, USA). The product of reps and weight was then calculated to create an overall volume load for each player.

7.4.3.2. Internal training load

Session rate of perceived exertion (sRPE) for each player was collected by a staff member between 10- and 45-mins post on-field training, resistance training, and games. When collecting the data, each player was asked to look at a sheet with the modified Borg-10 RPE scale including the verbal anchors (Borg, 1998) and inform the staff member how difficult they found each session relative to the scale. All data were recorded initially recorded manually, then entered into a digital database (Kitman Labs, Dublin, Ireland). The reported RPE was then multiplied by the duration of the session to calculate the session-RPE (sRPE) training load (Foster et al., 2001).

For each different load construct (i.e., TD, VHSR, sRPE, and RT) values were summed for each player for the 3, 7, and 28 days preceding each CMJ testing sessions. The 3-day timeframe was selected as previous research in elite athletes has suggested that neuromuscular status takes ~72 h to return to baseline following fatiguing stimuli (Cormack, Newton, & McGuigan, 2008; Gathercole, Stellingwerff, et al., 2015b). The 7- and 28-day timeframes were selected as the effect of cumulative workload for each of these timeframes on neuromuscular status is of interest to practitioners in field sports (Bourdon et al., 2017; Gabbett, 2016), and these findings may help to inform better practice and understanding of those load-response relationships.

7.4.3.3. CMJ testing

On testing days, players followed a previously described standardised warm-up (Howarth et al., 2021) before completing CMJs during the same 15-minute period (i.e., individual testing time varied less than 15 minutes across the season) and was always conducted between 09:00 and 09:45. CMJs were performed on a dual force plate system (NMP ForceDecks FD-4000–Vald Performance, Brisbane, Australia) connected to a laptop computer (Dell Latitude E5440) using protocols previously described (Howarth et al., 2021). Analysis of the CMJ force-time curves and generation of variables were completed using ForceDecks software (v2.0.7418, Vald Performance). Players received strong verbal encouragement during testing and immediate visual feedback post-CMJ on individual jump height (derived from flight time) through a digital display (ForceDecks Leaderboard v.2.0.7418, Vald Performance).

Each player was familiarised with the testing protocol (i.e., 3 repetitions of a single CMJ with hands on hips), having been involved in test-retest evaluation at the beginning of preseason along with previous exposure through this and other performance programs (Howarth et al., 2021). Every CMJ was observed by a member of the research team and any jumps deviating from standard protocol (e.g., jumpers attempted to "tuck" their legs during the flight phase, double jump/prejump, or did not land on the force plates) were excluded, and another jump performed to ensure 3 acceptable trials.

CMJ data were collected on Mondays and Thursdays throughout the entire season, including pre-season (42 weeks). **Figure 7.1** shows the typical weekly CMJ test schedule. The team played 32 matches (3 preseason and 29 in-season matches), with no testing conducted during scheduled non-training weeks. In-season matches occurred once per week and were played on Fridays or Saturdays. All players selected in an upcoming Friday match did not test on the Thursday of that week.

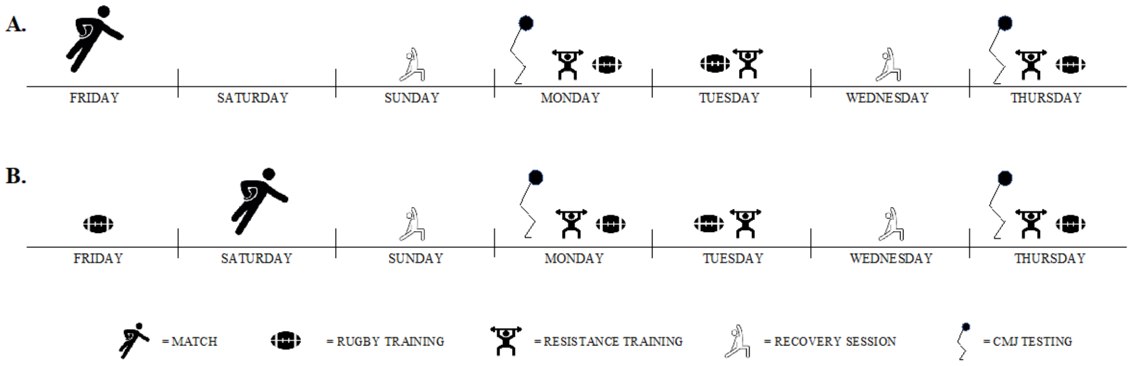

Figure 7.1 - Typical game and training week overview with scheduled jump testing.
A. Typical training week following a Friday game; B. Typical training week following a Saturday game

The CMJ variables used in this study were selected following an extensive process of examination of measurement characteristics, with the final group of variables being identified using principal components analysis (PCA) (Chapter 5). These variables are the most sensitive variables (minimum criterion: SNR >1.0) from each identified principal component (n = 15) across four different variable groupings (eccentric, concentric, landing, and composite variables) (Chapter 5). A full list of variables used to examine neuromuscular status for this study can be found in **Table 7.1**. To best elucidate the temporal nature of recovery from a game (Cormack, Newton, & McGuigan, 2008), Monday and Thursday tests were split into two different data sets for analysis. Monday testing was conducted to capture the response of players within 72-h post-match, a previously established timeframe for recovery of the neuromuscular system (Cormack, Newton, & McGuigan, 2008). Conversely, analysis of Thursday testing data aimed to capture neuromuscular status when all players were in a rested, well-prepared state (Howarth et al., 2023).

Table 7.1 – CMJ variables selected from PCA (Chapter 5).

Phase	PC	Variable Name
Eccentric	1	Eccentric Deceleration Phase Duration
	2	Force at Zero Velocity
	3	Countermovement Depth
	4	Eccentric Duration
	5	Eccentric Braking RFD – 100ms
Concentric	1	Concentric RPD – 100ms
	2	Concentric Mean Power
	3	P1 Concentric Impulse
	4	Concentric Mean Force
Landing	2	Landing RFD – 50ms
Composite	1	CMJ Stiffness
	2	Jump Height – Impulse Momentum
	3	Contraction Time/Eccentric Duration Ratio
	4	Total Work
	5	Braking Phase Duration/Concentric Duration Ratio

PC = Principal Component; PCA = Principal Component Analysis; Eccentric = downward movement or countermovement portion of the jump (includes unloading, braking, and deceleration phases); Concentric = upward movement or propulsive phase of the countermovement jump; RFD = rate of force development, RPD = rate of power development.

7.4.4. Statistical analysis

Linear mixed-effects models were used to discern which external or internal loads are associated with positive or negative variations in neuromuscular status throughout the season. Further, we investigated which interval of cumulation (i.e., 3-days, 7-days, or 28-days) had greater effects on these changes. This approach accounts for pseudoreplication, missing data, and allows for a mixture of both fixed and random effects. The random effects chosen as they represented individual or contextual factors (Jeffries et al., 2021) that could affect the response of the neuromuscular system. Individual factors are accounted for by entering them as a random effect. The contextual factor added to this analysis was position, as previous research has highlighted the different potential stressors to the neuromuscular system of players depending on their role on the field (Austin et al., 2011; Duthie et al., 2003; Tavares et al., 2017). The fixed effects tested were the cumulative loads over 3, 7, and 28 days for TD, VHSR, RT, and sRPE. The dependent variable for each analysis was the change in each CMJ metric from baseline testing. The value for each variable was established via the $Mean_3$ method, described previously (Howarth et al., 2021).

To examine the associations between individual and contextual factors (random effects), cumulative training loads (fixed effects) and changes in CMJ variables (dependant variables), 3-level linear mixed models were utilized. The random- and fixed-effects used in our study are shown in **Table 7.2**. When building the model, a "step up" strategy was used to ascertain how much the individual and contextual factors affected the dependent variables. To determine whether there was variation in the dependent variable, an unconditional model with a fixed intercept and two random factors was built. To choose the best fit model, visual comparison of the Akaike Information Criterion (AIC) was undertaken, where a lower AIC denotes a better model fit. After level 1 random effects were included, level 2 and level 3 random effects were added, and the models were then assessed once more. If the model and its fit (i.e., improving AIC) were judged to be significantly better than the preceding model, the random effects were kept in place.

Table 7.2 – Random and fixed effects used in mixed effects model specifications

Data Level		**Factors**	**Type**	**Classification**
Level 3	Clusters of Clusters (random effects)	Position (Front Row, Lock, Back Row, Half, Centre, Back Three)		
Level 2	Cluster of units (random effects)	Player		
Level 1	Unit of analysis	Individual season samples		
	Covariates (fixed effects)	Cumulative TD (3 days)	Continuous	m
		Cumulative VHSR (3 days)	Continuous	m
		Cumulative sRPE (3 days)	Continuous	AU
		Cumulative RT (3 days)	Continuous	kg
		Cumulative TD (7 days)	Continuous	m
		Cumulative VHSR (7 days)	Continuous	m
		Cumulative sRPE (7 days)	Continuous	AU
		Cumulative RT (7 days)	Continuous	kg
		Cumulative TD (28 days)	Continuous	m
		Cumulative VHSR (28 days)	Continuous	m
		Cumulative sRPE (28 days)	Continuous	AU
		Cumulative RT (28 days)	Continuous	kg

TD = total distance; VHSR = very high-speed running, sRPE = session rate of perceived exertion training load; RT = resistance training volume load.; m = metres; kg = kilograms, AU = arbitrary units.

An effect size correlation (d) between each factor was obtained by calculating the linear mixed models t statistic and degrees of freedom (df) and converting them. Cohen's d effect sizes were interpreted as <0.2, trivial; 0.2–0.6, small; .0.6–1.2, moderate; .1.2–2.0, large; and 2.0–4.0, very large. These respective effect sizes were chosen because they are the approximate translations of values from r correlation coefficients to d standardised differences in mean effect sizes (16). All statistical analysis was conducted in R (REF), and models were constructed and tested using lme4, a statistical package used for fitting and analysing mixed models (REF). The level for statistical significance was set at $p < 0.05$.

7.5. Results

Throughout the testing period, 1,287 CMJ tests across 28 athletes (46 ± 9 per player) were collected for analysis. Of these tests, 751 (27 ± 5 per player) were collected on Mondays, and 536 (19 ± 4 per player) collected on Thursdays. Throughout the season, players amassed a combined total of 3,395 individual on-field training involvements (121 ± 12 per player), 2,047 individual RT sessions (73 ± 12 per player), and 454 individual game involvements (16 ± 7 games per player at an average of 50 ± 23 minutes per game). **Table 7.3** shows the significant results of the unconditional models, delineating the impact of random effects (Athlete, and Position) on a simple intercept model for each CMJ variable. **Table 7.4** and **Table 7.5** show the significant results of the conditional models for Monday and Thursday, respectively, delineating the impact of the fixed effects (cumulative training and game loads) on each CMJ variable.

Table 7.3 - Difference in explanatory power of random effects on changes in CMJ variables.

	CMJ Stiffness (N/m)	Jump Height (Imp-Mom) (cm)	Contraction Time/ Eccentric Duration	Total Work (J)	Eccentric Deceleration Phase Duration (s)	Force at 0 Velocity (N)	Countermovement Depth (cm)	Eccentric Duration (ms)	Eccentric Braking RFD - 100ms (N/s/kg)	Concentric Rate of Power Development - 100ms (W/s/kg)	Concentric Mean Power (W/kg)	Part 1 of Concentric Impulse (Ns)	Concentric Mean Force (N/kg)	Landing RFD - 50ms (N/s/kg)
Athlete	*	*	*		*		*	*	*	*	*		*	*
Athlete + Position				**0.012** **0.02**		**0.03** **0.022**						**0.031** **0.037**		

Significance set at p<0.05. NA = no significant difference between the explanatory powers of random effects on unconditional intercept models. NB. Where no significant difference was noted, just "Athlete" was used as the random effect for mixed models. * = no significant difference between the explanatory power of the unconditional models (i.e., Athlete vs Athlete + Position)

Table 7.4 - Monday Jump Testing - Significant effects of training load on CMJ variables.

			CMJ Stiffness	Jump Height (Imp-Mom)	Contraction Time/ Eccentric Duration	Total Work	Braking Duration/ Concentric Duration	Eccentric Deceleration Phase Duration	Force at 0 Velocity	Counter Movement Depth	Eccentric Duration	Eccentric Braking RFD - 100ms	Concentric Rate of Power Development - 100ms	Concentric Mean Power	Part 1 of Concentric Impulse	Concentric Mean Force	Landing RFD - 50ms
TD	3-Day Total Distance	p-value					0.028					0.012	0.039	0.03		0.028	
		Cohen's D					0.082					-0.094	-0.077	-0.081		-0.082	
	7-Day Total Distance	p-value															
		Cohen's D															
	28-Day Total Distance	p-value				0.026											
		Cohen's D				0.083											
VHSR	3-Day Very High-Speed Running	p-value															
		Cohen's D															
	7-Day Very High-Speed Running	p-value															
		Cohen's D															
	28-Day Very High-Speed Running	p-value															
		Cohen's D															
sRPE	3-Day RPE x Time	p-value															
		Cohen's D															
	7-Day RPE x Time	p-value			0.034						0.035						
		Cohen's D			-0.079						0.079						
	28-Day RPE x Time	p-value	0.049							0.017	0.028					0.007	
		Cohen's D	0.073							-0.089	-0.082					0.101	
RT	3-Day RT Volume Load	p-value															
		Cohen's D															
	7-Day RT Volume Load	p-value															
		Cohen's D															
	28-Day RT Volume Load	p-value	0.003	0.015			0.042	0.01		0.005	0.04		0.035	0.012	0.038	0.018	
		Cohen's D	-0.112	-0.091			0.096	0.096		0.106	0.076		-0.078	-0.093	-0.077	-0.088	

Red numbers indicate inverse relationship. Significance set at p<0.05. Shaded variables have no relationships evident from mixed effects models examining cumulative load and CMJ variable changes. TD - Total distance; VHSR – Very high-speed running; RT – Resistance Training; RPE – Session Rate of Perceived Exertion; CMJ – countermovement jump. Blank cells represent no significant results arising from the model

Table 7.5 - Thursday Jump Testing - Significant effects of training load on CMJ variables.

			CMJ Stiffness	Jump Height (Imp-Mom)	Contraction Time/ Eccentric Duration	Total Work	Braking Duration/ Concentric Duration	Eccentric Deceleration Phase Duration	Force at 0 Velocity	Counter Movement Depth	Eccentric Duration	Eccentric Braking RFD - 100ms	Concentric Rate of Power Development - 100ms	Concentric Mean Power	Part 1 of Concentric Impulse	Concentric Mean Force	Landing RFD - 50ms
TD	3-Day Total Distance	p-value															
		Cohen's D															
	7-Day Total Distance	p-value															
		Cohen's D															
	28-Day Total Distance	p-value	0.021		0.004						0.018						
		Cohen's D	0.102		0.129						-0.105						
VHSR	3-Day Very High-Speed Running	p-value															
		Cohen's D															
	7-Day Very High-Speed Running	p-value															
		Cohen's D															
	28-Day Very High-Speed Running	p-value	0.038		0.015		0.03	0.034			0.032						
		Cohen's D	-0.092		-0.107		0.095	0.094			0.095						
sRPE	3-Day RPE x Time	p-value															0.019
		Cohen's D															0.104
	7-Day RPE x Time	p-value		0.002		<0.001			0.04					0.004	0.004		
		Cohen's D		-0.136		-0.181			-0.091					-0.127	-0.13		
	28-Day RPE x Time	p-value										0.01					
		Cohen's D										0.114					
RT	3-Day RT Volume Load	p-value				0.005											
		Cohen's D				-0.125											
	7-Day RT Volume Load	p-value				0.024	0.022										
		Cohen's D				0.101	-0.102										
	28-Day RT Volume Load	p-value															
		Cohen's D															

Red numbers indicate inverse relationship. Significance set at $p<0.05$. Greyed out variables have no relationships evident from mixed effects models examining cumulative load and CMJ variable changes. TD - Total distance; VHSR – Very high-speed running; RT = Resistance Training; RPE = Session Rate of Perceived Exertion; CMJ – countermovement jump. Blank cells represent no significant results arising from the model

Random effects revealed only 3 significant relationships for position with changes in CMJ variables: total work, force at zero velocity, and part 1 of concentric impulse. For all other CMJ variables, the individual athlete accounted for the same amount of variance arising from those contextual factors.

Evaluation of the load-response relationships with the Monday CMJ data shows 28-day RT had a significant effect in 10 out of the 15 mixed models: CMJ stiffness, jump height, eccentric deceleration phase duration, countermovement depth, eccentric duration, concentric rate of power development – 100 ms, concentric mean power, part 1 of concentric impulse, and concentric mean force. The effect of 28-day sRPE total load was significant in 4: CMJ stiffness, countermovement depth, eccentric duration, and concentric mean force. 3-day total distance had a significant response in 3 out of the 4 concentric variable models: concentric rate of power development – 100 ms, concentric mean power, and concentric mean force. Models for concentric mean force and eccentric duration both had significant effects to 3 cumulative load variables. Models for CMJ stiffness, countermovement depth, concentric rate of power development – 100 ms, and concentric mean power, each had 2.

The same evaluations on Thursday testing revealed different results, with 7-day sRPE total load having a significant effect in 5 different models: jump height, total work, force at zero velocity, concentric mean power, and part 1 of concentric impulse. Significant effect of 28-day VHSR had a significant effect in 4 models (CMJ stiffness, contraction time/eccentric duration ratio, eccentric deceleration phase duration, and eccentric duration), and 28-day TD had significant effect in 3 models (CMJ stiffness, contraction time/eccentric duration ratio). The mixed model for total work showed significant effects for 3 cumulative loads (7-day sRPE total load, 3-day resistance training volume load, and 7-day resistance training volume load). Models for CMJ stiffness, contraction time/eccentric duration ratio, and eccentric duration, all had significant effects from the same 2 cumulative loads: 28-day total distance and 28-day VHSR.

7.6. Discussion

The present study assessed how cumulative training load affected neuromuscular status in professional rugby players. The primary finding is the divergent effects of cumulative training load between data collected on Mondays (i.e., post-game) and Thursdays (i.e., recovered). Changes in neuromuscular status derived from Monday jump results were observed in response to both 28-day resistance training (RT) and 3-day total distance (TD). Conversely, different relationships were noted from Thursday jump data, where 28-day running volumes (TD and very high-speed running [VHSR]), and 7-day session rating of perceived exertion (sRPE) were associated with changes in neuromuscular response. Collectively, these results demonstrate the complex manner in which the neuromuscular system responds to different training loads and highlights the importance of using various training load measures to understand these changes.

Monday jump results revealed significant negative impacts of higher 3-day TD loads on concentric countermovement jump (CMJ) variables. These observations align with previous research, which reported reductions in CMJ variables up to 72 hours post-exhaustive exercise (Gathercole, Sporer, et al., 2015a) and following Australian Rules Football matches (Cormack, Newton, & McGuigan, 2008). Changes in discrete neuromuscular responses to specific cumulative training loads add context to these findings. In this study, three concentric variables from the CMJ (i.e., concentric rate of power development at 100ms, concentric mean power, and concentric mean force) were negatively influenced by higher 3-day TD, indicating that resultant fatigue affects the propulsive phase of jumping. Other studies have shown that peak muscle activation during CMJ occurs in the concentric (propulsive) phase (Sahrom et al., 2020). When taken with the current observations, it seems that reductions in both the overall propulsive mechanics and peak muscle activity of the posterior chain muscles during the CMJ are related to the 3-day TD prior to Monday testing. (Tavares et al., 2017; Thorpe et al., 2017)

Alongside the effects of 3-day TD noted on Mondays, athletes who have higher chronic RT loads experience significant changes in each CMJ grouping (composite, eccentric, and concentric). Indeed, a negative effect was observed in all four concentric variables, CMJ stiffness – a measure of stretch-shortening cycle efficiency (Jakobsen et al., 2012) – and jump height. Moreover, positive effects on eccentric variables indicate longer eccentric deceleration phase durations and increased countermovement depth. The effect of rapid (shorter) eccentric loading on concentric output is well-documented (Richter et al., 2014a; Sole et al., 2018) and likely explains these results. Reductions in CMJ stiffness can also be attributed to the concurrent reduction in concentric mean force and increase in countermovement depth, as this metric is calculated by dividing CMJ peak force by countermovement depth (N/m) (Hunter & Marshall, 2002). These interlinked changes suggest a more global neuromuscular fatigue experienced on Mondays by those engaged in higher chronic RT volumes.

It is notable that there was an absence of a negative neuromuscular response to chronic RT on Thursdays, as opposed to Mondays. Prior research has found that chronic resistance training enhances fatigue resistance in athletes, with variable resistance training promoting greater fatigue resistance compared to constant resistance training (Walker et al., 2013) These findings highlight the importance of assessing and managing neuromuscular fatigue, particularly in sports requiring concurrent strength and endurance training (Doma et al., 2017). The high emphasis on strength training within the overall program may explain the present results, as such emphasis has been reported in Northern Hemisphere rugby union programs (Jones, Smith, et al., 2017). It has been proposed that athletes who undergo significant resistance training during concurrent training might experience more acute muscle damage after prolonged running, potentially reducing muscle protein synthesis (Babault, 2023). While a clear explanation of the present results is difficult, they could be explained by the large emphasis being placed on strength training within the overall program. Accordingly, it is recommended that care be taken to titrate the balance between acute field and chronic strength training requirements to ensure athletes are more recovered when best performances are required. The lack of significant responses in Thursday models, along with the small effects, suggests that the amount of training was recoverable.

In contrast to Monday findings, Thursday data analysis revealed distinct cumulative load predictors, indicating temporal variations in neuromuscular status responses. The most impactful cumulative load was the 7-day sRPE total load, significantly negatively affecting 5 of the 12 CMJ variables. For 3 out of these 5 variables – total work, force at zero velocity, and part 1 of concentric impulse – the model includes position as a random effect, suggesting that variation in these results is driven by some contextual factor related to the demands of training and playing for each position (e.g., body composition, stature, levels of collision/contact) (Mitchell et al., 2016; Naughton et al., 2021; Quarrie & Hopkins, 2007; Roberts et al., 2008). Jump height and concentric mean power, the remaining variables, have been shown to reduce in response to acute fatigue in previous studies (Claudino et al., 2017; Gathercole, Stellingwerff, et al., 2015b). These position-specific demands likely explain the differential impact of sRPE load on neuromuscular performance across positions, highlighting the need for tailored training loads based on positional demands and individual characteristics (Andersson et al., 2008; McCall et al., 2018).

28-day TD and VHSR volumes showed opposing effects on CMJ stiffness, contraction time/eccentric duration ratio, and eccentric duration, with higher 28-day TD positively influencing these variables and higher 28-day VHSR having a negative effect. Previous research in rugby league players indicates that players who are better prepared for high-speed and high-intensity running are more resistant to neuromuscular fatigue arising from the same stimulus (Johnston et al., 2015). For further context, studies of rugby game play in different competitions (i.e., international vs club and northern- vs southern-hemisphere) shows significant differences in high-speed running (Austin et al., 2011; Cunniffe et al., 2009; Quarrie et al., 2013; Roberts et al., 2008). Similar to resistance training volume load, there is likely an optimal amount of VHSR in relation to overall training volume (TD) that allows players to enter competition without neuromuscular fatigue. Therefore, to optimise physical preparedness for competition, we recommend monitoring cumulative 28-day load and individual neuromuscular response to inform training load adjustment.

Although many significant effects are noted here, the effect sizes (Cohen's d statistic) are all in the 'trivial' range. These results are consistent with similar research in Australian Rules football players (Norris et al., 2021b) where statistical significance was noted between neuromuscular status measured with CMJ variables, but only with trivial effect sizes. The authors surmised that the timing of assessment (72 hours post-match) and the shorter longitudinal study (7 matches) were likely factors in reducing the noted effect (Norris et al., 2021b). To address this, we separated analyses into two distinct paradigms – Monday investigation examining the effects of cumulative load in the context of residual fatigue from the game, and Thursday investigating the 'low-frequency' fatigue effects of cumulative training loads when recovered – where our Monday testing fell inside of 72-hours post-match, the time course of recovery noted by previous research (Cormack, Newton, & McGuigan, 2008; Gathercole, Sporer, et al., 2015a). However, our results show a similar pattern. It must be noted that these studies were conducted in-situ and during a competition period, with staff that were conscious of and experienced in managing neuromuscular fatigue. Indeed, we suggest that practitioners should pay more attention to the statistical significance of these load-response relationships, particularly because these relationships are noted as significant when individual and contextual factors are accounted for in the statistical model (Jeffries et al., 2021).

In comparison to other similar studies, the present study adopted a more rigorous design. This study was characterised by a deliberate approach to objective selection of CMJ variables and more comprehensive analytical approaches (i.e., mixed-effects modelling). Utilising CMJ metrics chosen systematically based on measurement characteristics (reliability, sensitivity, and co-variance) provides practitioners with a unique understanding of CMJ variables and insights into combining and analysing training load and neuromuscular response data.

However, the study's limitations must be acknowledged. Using a single professional rugby team may limit generalisability. Competition involvement introduces a confounding influence, as players are managed to maximise performance, including neuromuscular fatigue management, observable in modest effect sizes. Internal or external load variables beyond this study’s scope—such as psychological and individual recovery factors—may also modulate neuromuscular outcomes and should be considered in future research.

7.7. Practical applications

Countermovement jump (CMJ) metrics serve as a valuable assessment tool for sport scientists, offering insights into athlete neuromuscular fatigue and readiness. The differential effects observed on different days—post-game (Monday) versus pre-game (Thursday)—suggest that timing assessments to align with these patterns can enhance the interpretation of neuromuscular responses and guide training adjustments. Resulting training and recovery strategies must be tailored to individual player roles, accounting for positional demands, body composition, and levels of collision/contact. This personalisation not only aids in mitigating the risk of neuromuscular fatigue but also optimises performance through targeted recovery strategies. Moreover, the use of neuromuscular assessment data to dynamically modulate training loads is imperative. Adjusting training intensity based on real-time assessments ensures that athletes maintain optimal readiness and minimal fatigue on game days. Educating both athletes and coaching staff on the impacts of training loads will further support this endeavour, emphasising the balance between high-intensity training and adequate recovery.

Chapter 8

Discussion

8.1. Thesis Findings

The body of work presented in this thesis outlines the development of a framework, which was then used to enhance our understanding of how the CMJ can be utilised as both a monitoring tool and a method for neuromuscular profiling in rugby union players. The findings around CMJ measurement characteristics and variable reduction may have direct implications for practitioners, and the framework presented can also be applied to understand test characteristics and refine variable selection in other scenarios within sports performance testing.

The findings of this thesis provide valuable insights into the use of CMJ in professional rugby players. In Chapter 3, a comprehensive analysis of 86 CMJ kinetic variables demonstrated high inter-day reliability, particularly when using the $Mean_3$ method compared to $Best_{JH}$. Importantly, no significant differences in relative reliability were observed across different testing conditions, providing an evidence-informed framework for practitioners to establish ecological validity in their settings. Chapter 4 revealed that many CMJ variables displayed greater week-to-week variability (signal) than inter-day variability (noise), with a substantial number of variables showing a SNR greater than 1.0, making them useful for monitoring athletes across a season. Chapter 5 used principal component analysis (PCA) to identify 2-5 key variables within each CMJ phase, reducing data redundancy while preserving essential insights for long-term monitoring. Chapter 6 outlined a systematic process for selecting CMJ variables through agnostic statistical approaches, facilitating evidence-based frameworks for practitioners. Finally, Chapter 7 highlighted the differential effects of cumulative training loads on neuromuscular status, with distinct relationships observed depending on the timing of CMJ testing (post-game vs. recovered). These findings underscore the complex responses of the neuromuscular system to various training loads and reinforce the importance of tailored monitoring strategies.

Through the process of examining the background literature and developing the research aims and methodology for this thesis, it became evident that several common assumptions in this type of research—some of which were present during the initial stages of this project—can negatively impact decision-making by both researchers and practitioners. These assumptions include:

i) There is one set of variables that provide the most meaningful information from a CMJ.
ii) CMJ patterns are directly correlated with performance.
iii) Measures of reliability are the most important measurement characteristic for selecting CMJ test variables, and these variables can be classified as "good" or "bad" based solely on reliability metrics.

While these assumptions aim to simplify the decision-making process for practitioners, there were severe limitations in this approach that could hinder the utilisation and interpretation of this type of information. This thesis critically evaluated the relevant background literature related to these concepts, including statistical methods, and presents alternative approaches for assessing data more comprehensively (e.g., considering a broader range of CMJ variables). These alternative methods address some of the previous (flawed) assumptions and offer an improved framework to guide expert decision-making. Specifically, this thesis proposes that: 1) reliability is not a binary construct and should be considered in the context of test/variable sensitivity; 2) the usefulness of variables is context-specific and may differ in various situations (e.g., acute vs. chronic measurements as presented in this thesis); and 3) assuming direct links to performance may be implausible, but CMJ testing profiles can provide important insights into underlying capacities that support performance. Unlike common assumptions in this field, the framework developed here is more agnostic and less absolute, allowing for a more nuanced perspective and better support for expert decision-making.

This following discussion section will expand on several key concepts, including insights into the measurement characteristics of countermovement jump variables and their relationships with other measurements within the context of a rugby union season. It will conclude by presenting the framework developed throughout this thesis—a framework that can be applied in various contexts to assist with data reduction and create streamlined systems, while still incorporating essential context and practitioner expertise.

8.2. Rethinking measurement characteristic constructs

8.2.1. Reliability

8.2.1.1. Number of trials and data treatment methods

This thesis highlights several important methodological factors to consider in reliability measurements. Firstly, we found that the inter-day CV for all CMJ variables was lower when using the mean of three jump trials ($Mean_3$) compared to the single best jump height ($Best_{JH}$). Therefore, if practitioners aim to obtain the most reliable data, it is recommended that they use results from multiple maximal trials rather than relying solely on the 'best' result. Additionally, the high relative reliability as measured by intraclass correlation coefficients (ICC) across all different combinations of testing days shows that the rank-order of athletes within testing did not change within the first week of training. These combined results show that both absolute results for variables and the rank-order of athletes was not affected by the first week of training, giving confidence to practitioners that conducting reliability testing on any 2-day combination in the first week of pre-season is appropriate for attaining clear reliability results.

8.2.1.2. Motivation and maximal effort

Ensuring athletes perform CMJs with maximal effort and sufficient motivation is critical for collecting valid and reliable data. While we did not directly compare protocols with varying levels of motivation in this study, we implemented several strategies to enhance motivation and achieve maximal effort in all jumps. These included providing immediate feedback on performance, such as displaying jump heights on a digital leaderboard, and fostering a competitive atmosphere among athletes. Such an environment ensures athletes are fully engaged and striving to deliver their best effort, which is essential for obtaining accurate data that reflect their true neuromuscular status and performance capabilities. This competitive, feedback-driven approach likely contributed to the lower variability (CV) in the measured variables compared to previous studies, highlighting the value of integrating motivational elements into testing protocols to optimise the quality and accuracy of performance assessments in professional sports settings.

8.2.1.3. Arbitrary thresholds for dichotomising reliability

There is a common trend in sports science literature to dichotomise test/monitoring tools as either 'reliable' or 'not reliable' based on a single, absolute threshold—often a coefficient of variation (CV) of 10%. Claudino et.al. (Claudino et al., 2017) stated that 'variables with a large CV are less likely (odds ratio) to detect statistically significant differences during repetitive measurements', citing a 1998 paper on ecosystem replicability by Patrik Kraufvelin (Kraufvelin, 1998). However, one of Kraufvelin's final conclusions states the following:

> *"A variable that is highly variable might therefore still be very useful as an effective test endpoint, if the treatment causes a response large enough. We should thus not only look for less variable test variables. We might as well still have use for highly variable test variables as long as they have an inherent tendency to show large*

deviations from the control mean once subjected to stress. A variable with a low CV is still of limited use if the corresponding deviations in the treatments may be expected to be very small also" (Kraufvelin, 1998).

This statement directly challenges the idea that a variable's usefulness can be judged solely on its absolute reliability. While baseline variability is important, it must be considered in the context of the changes measured over time. Analyses such as effect sizes based on specific interventions, mixed models, and simple signal-to-noise ratios that account for expected variability over time are far more valuable in assessing the utility of a variable in informing decision-making around athlete preparation. Further, labelling 'levels' of variation (e.g. "large", "small") is also unhelpful, as this simplification overlooks sensitivity and can therefore lead to poor interpretation of data.

8.2.2. Sensitivity

Understanding the measurement characteristics in terms of both reliability and sensitivity is crucial for determining the utility and application of a given variable or test. Chapter 5 offers valuable insights for practitioners working in professional athlete health and performance, as it identified CMJ variables with sufficient sensitivity that exceeded the inherent noise of the CMJ variables. Such analysis can inform the usefulness of these variables in monitoring athletes' neuromuscular status and readiness throughout a competitive season.

8.2.2.1. Ecologically valid constructs of sensitivity

The present thesis aimed to assess the sensitivity of CMJ variables in an ecologically valid environment, ensuring the results would be most relevant and applicable to athletes being tested in that setting. This was achieved by evaluating the variability of CMJ variables across a season and comparing it to baseline reliability at the start of the season to calculate a signal-to-noise ratio (SNR). However, it should be acknowledged that sensitivity can be assessed in different ways, depending on the needs of researchers or practitioners, and this may yield different results based on the context in which it is applied. For example, sensitivity might be assessed in response to an acute training intervention, such as immediately following heavy resistance training. This type of acute assessment of variable sensitivity would likely produce different results from the season-long SNR approach used here but could be more relevant for those specific situations. Therefore, researchers should avoid making generalisations about test/variable sensitivity and rather, discuss the context in which their findings are developed and applied. The goal of the present thesis was to assess the sensitivity of variables throughout a rugby season, a scenario in which practitioners aim to avoid overtraining athletes to ensure they are prepared for games. In-season measurements were taken when athletes were not acutely fatigued (i.e., on Thursdays each week). This was done to provide information about variable sensitivity in this exact context, which could be useful for rugby union practitioners seeking to use CMJ data to inform decision-making around individual player programming.

8.2.2.2. Effect of data treatment methods on sensitivity

This study differentiates itself from other investigations of CMJ variable changes primarily through its comprehensive approach to analysing CMJ variables using three distinct data treatment methods: $Mean_3$, $Best_{JH}$, and $Best_{FTCT}$. Unlike previous studies that often rely on a single data treatment method or arbitrary reliability cutoffs (e.g., CV <10%), this study incorporates a comparative analysis of multiple methods to determine the sensitivity of CMJ variables. The findings from Chapter 4 suggest that practitioners should consider data treatment methods that improve the sensitivity of CMJ variables. In this study, the Mean3 and $Best_{FTCT}$ methods produced more sensitive results compared to $Best_{JH}$. Similar to the reliability results, practitioners should consider the analytical approaches and which data treatment methods provide the most sensitive results in their specific environments, thereby enhancing their ability to assess changes in athletes' neuromuscular function and performance.

8.2.2.3. Considering the strength of the signal

When assessing measurement characteristics, such as reliability and sensitivity, the variability in these results is often overlooked. In this thesis, this issue was addressed by identifying specific CMJ variables with non-overlapping 95% CIs for signal (i.e., week-to-week variability throughout the season) and noise (absolute test/re-test reliability). Using CIs in this manner provided a statistical measure of the precision of the estimated signal and noise. When CIs did not overlap, it identified a statistically significant difference, offering stronger evidence that the variable is sensitive to changes in athlete status. By incorporating CIs into the analysis, practitioners can better contextualise and enhance the utility of CMJ variables in athlete monitoring, making the data more meaningful for tracking individual progress and supporting informed decision-making. These findings help practitioners more accurately identify variables that demonstrate true changes in response to training and competition loads. This methodological rigor ensures that the observed variability is not merely attributable to random error but reflects genuine physiological or performance changes. Consequently, this approach minimises the likelihood of false positives (identifying a change when none exists) and false negatives (failing to identify a real change), which is essential in high-performance settings where decisions based on monitoring data can significantly impact athlete health and performance.

8.2.3. Co-variance

Creating parsimonious systems, where the data is distilled down to the most important and actionable items, is a critical consideration for practitioners. This is particularly relevant in

CMJ testing, where force platforms and related software can produce over 150 variables for each jump. By examining shared co-variance and condensing the extensive range of CMJ variables into a more manageable set of principal components (as completed in Chapter 6), practitioners can interpret the neuromuscular status of athletes more efficiently and accurately. This streamlined approach simplifies decision-making, enhances monitoring precision, and supports more timely, informed adjustments to training and injury prevention strategies.

8.2.3.1. Minimising bias in variable reduction

Previous research aimed at reducing the number of CMJ variables used in analysis has often relied on pre-selecting a subset of variables based on subjective or arbitrary criteria, which may lead to the exclusion of useful variables. In contrast, the work in this thesis used phase-specific application of PCA to achieve variable reduction. This agnostic approach ensures that all available variables are considered, allowing for a more inclusive and unbiased identification of principal components. Indeed, the pre-selection of variables in these studies is often based on common usage or assumed relevance, which can unintentionally exclude important variables or include those that add little value.

8.2.3.2. Maintaining phase specific information during data reduction

The methods used in this thesis provide a nuanced understanding of CMJ data by analysing variables within distinct phases of the jump—eccentric, concentric, landing, and composite. For professionals working with elite athletes, this phase-specific approach allows for more precise interpretations and targeted interventions. By keeping individual phases distinct in the data reduction process, practitioners can maintain a comprehensive yet concise monitoring system that captures key performance metrics, enabling interventions that address specific aspects of an athlete's jump mechanics.

8.3. Contextual factors for CMJ variable selection

For practitioners using various tests and technologies to assess performance, the framework and findings presented in these investigations offer a rigorous and effective method for analysing and interpreting data. These results are particularly relevant for those measuring CMJ on force platforms, providing valuable insights for understanding neuromuscular status. While the large amount of information can seem overwhelming (Coutts, 2017) and opinions on what variables to use are often presented as strong evidence with an air of unquestionable certainty. (Bishop et al., 2023; Bishop et al., 2021). Such dogmatic approaches, from authoritative voices in scientific literature, are unhelpful in advancing overall understanding and hinder practitioners from embracing nuance to truly enhance decision-making for the athletes they serve. The agnostic and systematic approach presented in this work aims to enhance understanding of each variable so that objective decisions can be made when selecting variables. This approach places nuanced insights in the hands of practitioners without overwhelming the decision-making process with redundant data.

In Chapter 7, the investigation into the effects of cumulative load on neuromuscular status distinguishes random and fixed effects related to CMJ variables in two different conditions: the 'fatigued' state (Monday) and the 'recovered' state (Thursday). Distinct effects on CMJ performance were observed between the ‘fatigued’ (Monday) and ‘recovered’ (Thursday) conditions, highlighting the dynamic nature of neuromuscular status. Additionally, within a given condition (i.e., fatigued or recovered), differential effects of training load were observed between different phases, and even among individual variables within a phase, which reflects the nuanced sensitivities of the fitness-fatigue continuum in professional rugby players.

8.3.1. Limitations

This investigation's focus is on a single group of athletes, thereby limiting the generalisability of these results. However, it is important to note that this work was conducted with high-performance, professional athletes, which is unique. This provides strong support for the application of these frameworks in similar elite-level groups, where the insights can be adapted for use in different contexts and athlete populations to better understand their specific applications. Future research should examine a range of stimuli within similar frameworks, such as situational load (e.g., scheduling), mechanical loads (e.g., acceleration, deceleration, and contact), and athlete responses like perceptual wellbeing. Adopting systematic and unbiased approaches can provide a clearer understanding of the value and impact of these monitoring tools, both as standalone measures and as part of a holistic monitoring approach.

Ratio-based metrics are widely used by CMJ measurement software programs to characterize neuromuscular function. These measures can introduce several statistical limitations that warrant caution. For instance, small or highly variable denominators (e.g., body mass or a brief time interval) may inflate measurement noise and obscure true physiological changes, particularly when repeated assessments are conducted over short time scales (Atkinson & Nevill, 1998). Ratios can also diminish critical information regarding absolute performance levels, masking potentially meaningful shifts in jump height or force output (Velleman & Wilkinson, 1993). Furthermore, statistical assumptions underpinning ratio-based analyses—such as homoscedasticity—are often violated, leading to unreliable inferential outcomes unless carefully addressed with appropriate transformations (e.g., log transformations) or modelling approaches (Bland & Altman, 1995; Packard & Boardman, 2008). Consequently, interpreting CMJ variables solely via ratio metrics may oversimplify complex interactions between numerator and denominator, emphasising the need to complement ratio data with absolute measures, repeated-measures models, or robust normalisation procedures in order to capture the multifaceted nature of neuromuscular function, such as those employed in this research.

8.3.2. Practitioner recommendations

Arising from this research are a number of recommendations that will aid in achieving this systematic and agnostic process that refines their athlete monitoring. **Figure 8.1** contains the key points from the practical applications in each study and those that were seen as critical elements to retaining the ecological validity and fidelity of the measurement characteristics being investigated. Practitioners looking to employ this framework, it is suggested that these elements are foundational to the analysis.

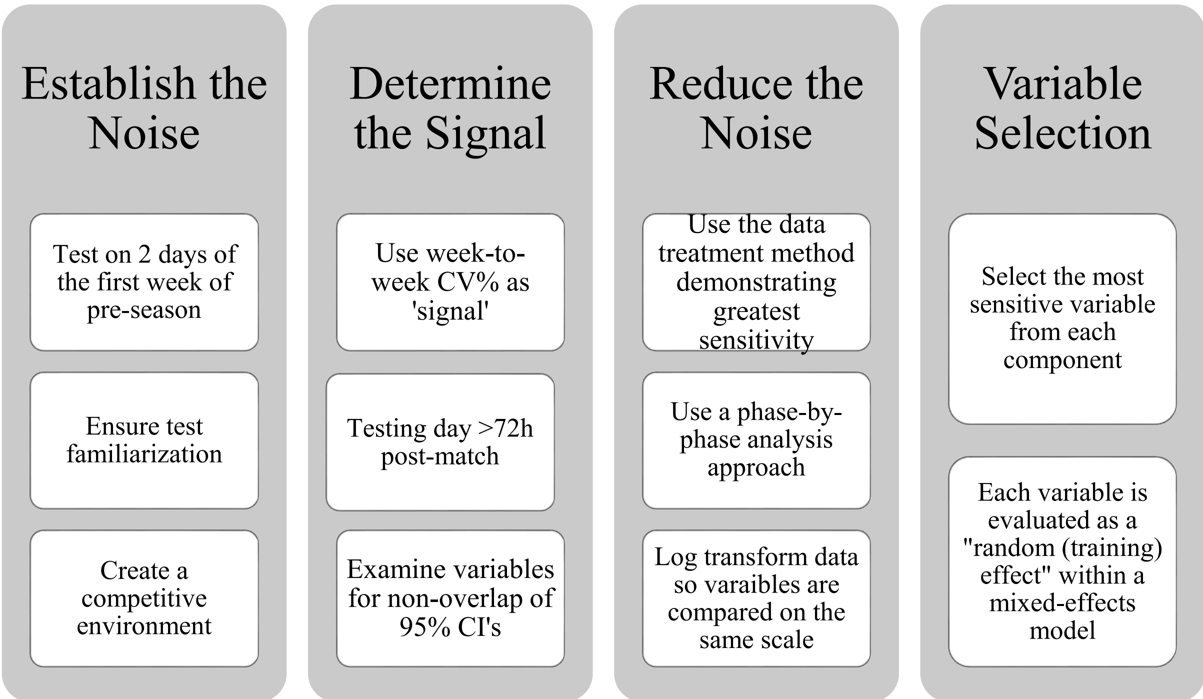

Figure 8.1 – Practical recommendations for practitioners seeking to employ this framework in a professional team environment

8.4. Entia non sunt multiplicanda praeter necessitate

In a 2014 editorial, Aaron Coutts presents the underlying principle of Occam's Razor:

‘*Entia non sunt multiplicanda praeter necessitate* '

In English, this translates to 'More things should not be used than are necessary,' and this principle poses a persistent challenge in modern professional sports, where vast amounts of data and information are readily available. The thinking behind Occam's Razor (and the 2014 Coutts editorial) was a guiding principle in the development of this work, aiming to achieve 'intelligent parsimony.' This approach retains essential information and nuance while eliminating unnecessary data. In this pursuit, it is acknowledged that all CMJ variables may hold value in certain situations and should not be excluded arbitrarily. Instead, variables should be included or excluded based on a validated understanding of their application in specific contexts (such as athlete monitoring throughout a rugby union season). Structured frameworks can be used to empower practitioners in their decision-making, supporting the principle that more things should not be used than are necessary.

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Appendices

Appendix 1. Inter-day absolute reliability (CV) and 95% confidence intervals of countermovement jump variables using Mean$_3$

Variables	Mean (±SD)	Condition 1 Mon-Tue		Condition 2 Mon-Thu		Condition 3 Tue-Thu		Condition 4 Mon-Mon		Condition 5 Mon-Tue-Thu	
Body Weight (kg)	**102.8 (12)**	**0.7**	(0.7 - 0.9)	**0.9**	(0.8 - 1.1)	**0.9**	(0.8 - 1.1)	**1.1**	(1.0 - 1.3)	**0.7**	(0.7 - 0.9)
Countermovement Depth (cm)	**44.3 (7)**	**5.4**	(5.0 - 6.6)	**4.1**	(3.8 – 5.0)	**4.2**	(3.9 - 5.1)	**4.4**	(4.0 - 5.3)	**5.5**	(5.1 - 6.7)
Jump Height - Flight Time (cm)	**44.5 (6)**	**2.8**	(2.6 - 3.4)	**3.1**	(2.9 - 3.8)	**2.7**	(2.5 - 3.3)	**3.5**	(3.2 - 4.3)	**2.8**	(2.6 - 3.4)
Jump Height - Impulse Momentum (cm)	**36 (6)**	**6.9**	(6.3 - 8.3)	**5.2**	(4.8 - 6.3)	**6.0**	(5.5 - 7.2)	**7.4**	(6.8 – 9.0)	**6.9**	(6.4 - 8.4)
Lower Limb Stiffness ($N.m^{-1}$)	**5632 (1697)**	**7.5**	(6.9 – 9.0)	**7.1**	(6.5 - 8.6)	**7.5**	(6.9 - 9.1)	**8.9**	(8.2 - 10.8)	**7.6**	(7.0 - 9.2)
CMJ Stiffness ($N.m^{-1}$)	**6035 (1637)**	**6.6**	(6.1 – 8.0)	**4.8**	(4.4 - 5.8)	**6.5**	(5.9 - 7.8)	**6.3**	(5.8 - 7.7)	**6.7**	(6.1 - 8.1)
Total Work (J)	**1265 (180)**	**3.4**	(3.1 - 4.1)	**2.7**	(2.5 - 3.3)	**3.2**	(2.9 - 3.8)	**3.6**	(3.3 - 4.3)	**3.4**	(3.2 - 4.2)
RSI modified ($m.s.^{-1}$)	**0.56 (0.09)**	**5.2**	(4.8 - 6.3)	**6.1**	(5.6 - 7.4)	**5.3**	(4.9 - 6.4)	**7.3**	(6.7 - 8.8)	**5.3**	(4.9 - 6.4)
Flight Time/ Contraction Time Ratio	**0.76 (0.10)**	**4.3**	(4.0 - 5.2)	**4.9**	(4.5 - 5.9)	**4.4**	(4.1 - 5.3)	**5.7**	(5.2 - 6.9)	**4.4**	(4.0 - 5.3)
Eccentric/ Concentric Duration (%)	**184 (19)**	**4.7**	(4.4 - 5.7)	**5.3**	(4.9 - 6.4)	**4.2**	(3.9 - 5.1)	**4.8**	(4.4 - 5.8)	**4.8**	(4.4 - 5.8)
Eccentric/ Concentric Mean Force (%)	**52 (3)**	**1.7**	(1.6 - 2.1)	**1.7**	(1.5 – 2.0)	**1.8**	(1.6 - 2.2)	**2.3**	(2.1 - 2.8)	**1.7**	(1.6 - 2.1)
Concentric Impulse 100ms/ Concentric Impulse Ratio	**0.48 (0.08)**	**4.7**	(4.3 - 5.6)	**4.8**	(4.4 - 5.8)	**4.7**	(4.3 - 5.7)	**4.6**	(4.3 - 5.6)	**4.7**	(4.3 - 5.7)
Eccentric Peak Power/ Concentric Peak Power Ratio	**0.45 (0.12)**	**10.8**	(9.9 – 13.0)	**11.2**	(10.3 - 13.6)	**9.4**	(8.6 - 11.3)	**10.5**	(9.7 - 12.8)	**10.9**	(10.1 - 13.2)
P2 Concentric Impulse/ P1 Concentric Impulse Ratio	**0.60 (0.12)**	**5.9**	(5.4 - 7.1)	**7.0**	(6.5 - 8.5)	**6.0**	(5.6 - 7.3)	**6.2**	(5.7 - 7.6)	**5.9**	(5.5 - 7.2)
Time to Braking Phase (s)	**0.18 (0.05)**	**12.9**	(11.9 - 15.5)	**13.4**	(12.4 - 16.3)	**12.6**	(11.6 - 15.2)	**13.6**	(12.5 - 16.5)	**13.0**	(12.0 - 15.8)
Eccentric Duration (ms)	**521 (84)**	**5.0**	(4.6 - 6.1)	**5.6**	(5.2 - 6.8)	**5.0**	(4.6 – 6.0)	**5.8**	(5.4 - 7.1)	**5.1**	(4.7 - 6.2)
Braking Phase Duration (s)	**0.34 (0.05)**	**5.3**	(4.9 - 6.4)	**5.4**	(4.9 - 6.5)	**4.5**	(4.1 - 5.4)	**7.0**	(6.4 - 8.5)	**5.4**	(5.0 - 6.5)
Eccentric Acceleration Phase Duration (s)	**0.33 (0.06)**	**6.7**	(6.2 - 8.1)	**7.5**	(6.9 – 9.0)	**6.9**	(6.3 - 8.3)	**6.8**	(6.2 - 8.3)	**6.7**	(6.2 - 8.1)
Eccentric Deceleration Phase Duration (s)	**0.19 (0.04)**	**5.6**	(5.1 - 6.7)	**4.9**	(4.5 – 6.0)	**5.5**	(5.1 - 6.7)	**7.8**	(7.1 - 9.4)	**5.6**	(5.2 - 6.8)
Concentric Duration (ms)	**283 (33)**	**3.2**	(3.0 - 3.9)	**2.7**	(2.5 - 3.3)	**2.6**	(2.4 - 3.2)	**3.0**	(2.8 - 3.7)	**3.3**	(3.0 – 4.0)
Contraction Time (ms)	**804 (111)**	**3.9**	(3.6 - 4.7)	**4.1**	(3.8 – 5.0)	**3.8**	(3.5 - 4.6)	**4.5**	(4.2 - 5.5)	**3.9**	(3.6 - 4.8)
Concentric Time to Peak Force (ms)	**29 (44)**	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA
Movement Start to Peak Force (s)	**0.53 (0.10)**	**9.9**	(9.1 - 11.9)	**10.7**	(9.8 - 12.9)	**8.3**	(7.6 – 10.0)	**10.2**	(9.4 - 12.4)	**10.1**	(9.3 - 12.2)

Variables	Mean (±SD)	Condition 1 Mon-Tue	Condition 2 Mon-Thu	Condition 3 Tue-Thu	Condition 4 Mon-Mon	Condition 5 Mon-Tue-Thu
Movement Start to Peak Power (s)	**0.74 (0.11)**	**4.2** (3.9 - 5.1)	**4.4** (4.1 - 5.4)	**4.1** (3.8 - 4.9)	**4.9** (4.5 - 5.9)	**4.3** (3.9 - 5.2)
Flight Time (ms)	**601 (43)**	**1.4** (1.3 - 1.7)	**1.5** (1.4 - 1.9)	**1.4** (1.3 - 1.7)	**1.7** (1.6 - 2.1)	**1.4** (1.3 - 1.7)
Minimum Eccentric Force (N)	**161 (137)**	**37.9** (34.9 - 45.8)	**45.4** (41.8 - 55.2)	**30.8** (28.4 - 37.5)	**43.2** (39.7 – 53.0)	**37.2** (34.2 - 45.2)
Eccentric Mean Force (N)	**1011 (118)**	**0.7** (0.7 - 0.9)	**0.9** (0.8 - 1.1)	**0.9** (0.8 - 1.1)	**1.1** (1.0 - 1.4)	**0.7** (0.7 - 0.9)
Eccentric Mean Braking Force (N)	**1269 (155)**	**3.1** (2.9 - 3.8)	**3.4** (3.1 - 4.1)	**2.7** (2.5 - 3.2)	**4.0** (3.7 - 4.8)	**3.2** (2.9 - 3.8)
Eccentric Mean Deceleration Force (N)	**1932 (337)**	**4.0** (3.7 - 4.8)	**4.1** (3.8 – 5.0)	**3.9** (3.6 - 4.7)	**5.2** (4.8 - 6.3)	**4.1** (3.8 - 4.9)
Eccentric Peak Force (N)	**2566 (406)**	**4.3** (4.0 - 5.2)	**4.3** (4.0 - 5.2)	**4.1** (3.8 - 4.9)	**5.6** (5.2 - 6.9)	**4.3** (3.9 - 5.2)
Eccentric Peak Force/ BM (N.kg^{-1})	**25 (2.5)**	**4.0** (3.7 - 4.9)	**4.3** (4.0 - 5.3)	**3.8** (3.5 - 4.6)	**5.6** (5.1 - 6.8)	**4.0** (3.7 - 4.9)
Force at Zero Velocity (N)	**2534 (404)**	**4.1** (3.8 – 5.0)	**4.0** (3.7 - 4.9)	**4.0** (3.7 - 4.9)	**5.2** (4.8 - 6.4)	**4.1** (3.8 – 5.0)
Concentric Mean Force (N)	**1974 (272)**	**2.0** (1.9 - 2.4)	**1.7** (1.5 – 2.0)	**2.0** (1.8 - 2.4)	**2.3** (2.1 - 2.8)	**2.0** (1.9 - 2.5)
Concentric Mean Force/ BM (N.kg^{-1})	**19 (1.3)**	**1.7** (1.6 - 2.1)	**1.7** (1.5 – 2.0)	**1.8** (1.6 - 2.1)	**2.4** (2.2 - 2.9)	**1.8** (1.6 - 2.1)
Concentric Peak Force (N)	**2555 (395)**	**3.4** (3.2 - 4.1)	**2.9** (2.6 - 3.5)	**3.9** (3.6 - 4.8)	**4.2** (3.9 - 5.2)	**3.4** (3.1 - 4.1)
Concentric Peak Force/ BM (N.kg^{-1})	**25 (2.3)**	**3.2** (2.9 - 3.8)	**3.0** (2.7 - 3.6)	**3.6** (3.3 - 4.4)	**4.2** (3.9 - 5.1)	**3.2** (2.9 - 3.8)
Force at Peak Power (N)	**2042 (279)**	**2.1** (2.0 - 2.6)	**2.7** (2.5 - 3.2)	**2.1** (1.9 - 2.5)	**2.2** (2.0 - 2.7)	**2.2** (2.0 - 2.6)
Peak Net Takeoff Force/ BM (N.kg^{-1})	**15 (2.4)**	**5.7** (5.3 - 6.9)	**5.8** (5.3 – 7.0)	**6.2** (5.7 - 7.5)	**8.1** (7.4 - 9.8)	**5.7** (5.2 - 6.9)
Peak Landing Force (N)	**8165 (2072)**	**11.6** (10.7 – 14.0)	**13.5** (12.4 - 16.3)	**10.4** (9.6 - 12.6)	**13.1** (12.1 - 16)	**11.8** (10.9 - 14.3)
Peak Landing Force/ BM (N)	**80 (21)**	**11.3** (10.5 - 13.7)	**13.4** (12.3 - 16.2)	**10.1** (9.3 - 12.3)	**12.9** (11.9 - 15.7)	**11.5** (10.6 - 13.9)
Landing Net Peak Force/ BM (N.kg^{-1})	**70 (21)**	**13.0** (12.0 - 15.6)	**15.3** (14.1 - 18.6)	**11.6** (10.7 - 14.1)	**15.0** (13.8 - 18.3)	**13.1** (12.1 - 15.9)
Jump Height (FT) Relative Peak Landing Force (N.cm^{-1})	**187 (53)**	**11.9** (11.0 - 14.3)	**14.0** (12.9 - 17)	**10.3** (9.4 - 12.4)	**13.9** (12.8 - 16.9)	**12.1** (11.1 - 14.6)
Eccentric Unloading Impulse (Ns)	**167 (27)**	**5.2** (4.8 - 6.3)	**6.4** (5.9 - 7.7)	**4.6** (4.2 - 5.5)	**6.3** (5.8 - 7.7)	**5.3** (4.9 - 6.4)
Eccentric Braking Impulse (Ns)	**84 (16)**	**10.5** (9.7 - 12.7)	**11.0** (10.1 - 13.3)	**8.9** (8.2 - 10.8)	**12.3** (11.3 - 14.9)	**10.7** (9.8 - 12.9)
Eccentric Deceleration Impulse (Ns)	**167 (27)**	**5.1** (4.7 - 6.2)	**6.4** (5.9 - 7.7)	**4.5** (4.1 - 5.4)	**6.4** (5.9 - 7.7)	**5.2** (4.8 - 6.3)
Concentric Impulse 50ms (Ns)	**72 (15)**	**5.8** (5.4 – 7.0)	**5.9** (5.4 - 7.1)	**6.3** (5.8 - 7.6)	**7.3** (6.7 - 8.9)	**5.8** (5.4 – 7.0)
Concentric Impulse 100ms (Ns)	**131 (28)**	**5.0** (4.6 - 6.1)	**5.3** (4.9 - 6.4)	**5.7** (5.3 - 6.9)	**6.4** (5.9 - 7.8)	**5.0** (4.6 - 6.1)

Variables	Mean (±SD)	Condition 1 Mon-Tue	Condition 2 Mon-Thu	Condition 3 Tue-Thu	Condition 4 Mon-Mon	Condition 5 Mon-Tue-Thu
Concentric Impulse (Ns)	**271 (33)**	**3.5** (3.2 - 4.2)	**2.3** (2.1 - 2.8)	**3.1** (2.9 - 3.8)	**3.5** (3.2 - 4.2)	**3.5** (3.2 - 4.3)
P1 Concentric Impulse (Ns)	**171 (25)**	**3.9** (3.6 - 4.7)	**3.5** (3.2 - 4.3)	**3.9** (3.6 - 4.8)	**4.6** (4.3 - 5.6)	**3.9** (3.6 - 4.7)
P2 Concentric Impulse (Ns)	**100 (17)**	**5.3** (4.9 - 6.4)	**4.8** (4.5 - 5.9)	**4.9** (4.5 - 5.9)	**4.6** (4.3 - 5.6)	**5.4** (5.0 - 6.5)
Landing Impulse (Ns)	**60 (25.4)**	**18.3** (16.9 – 22.0)	**21.5** (19.8 – 26.0)	**15.8** (14.6 - 19.1)	**24.9** (23.0 - 30.3)	**18.4** (17.0 - 22.3)
Eccentric Mean Power (W)	**862 (134)**	**5.9** (5.4 - 7.1)	**6.7** (6.2 - 8.1)	**4.9** (4.5 - 6)	**7.3** (6.7 - 8.8)	**6.0** (5.5 - 7.2)
Eccentric Mean Power / BM (W.kg.$^{-1}$)	**8.4 (1)**	**5.7** (5.2 - 6.8)	**6.5** (6.0 - 7.9)	**4.8** (4.4 - 5.8)	**6.9** (6.4 - 8.4)	**5.8** (5.3 – 7.0)
Eccentric Peak Power (W)	**2481 (613)**	**9.0** (8.3 - 10.9)	**10.3** (9.5 - 12.4)	**8.9** (8.2 - 10.7)	**10.4** (9.6 - 12.6)	**9.2** (8.4 - 11.1)
Eccentric Peak Power BM (W.kg.$^{-1}$)	**24 (5)**	**8.7** (8.0 - 10.4)	**10.2** (9.4 - 12.3)	**8.7** (8.0 - 10.5)	**10.2** (9.4 - 12.4)	**8.8** (8.1 - 10.6)
Concentric Mean Power (W)	**2896 (459)**	**4.7** (4.3 - 5.6)	**3.8** (3.5 - 4.6)	**4.5** (4.1 - 5.4)	**5.7** (5.2 - 6.9)	**4.7** (4.3 - 5.7)
Concentric Mean Power/ BM (W.kg.$^{-1}$)	**28 (3.3)**	**4.5** (4.1 - 5.4)	**4.0** (3.7 - 4.8)	**4.3** (4.0 - 5.2)	**5.8** (5.4 - 7.1)	**4.5** (4.1 - 5.4)
Peak Power (W)	**5088 (754)**	**4.4** (4.0 - 5.3)	**3.2** (3.0 - 3.9)	**3.9** (3.6 - 4.8)	**4.8** (4.4 - 5.8)	**4.5** (4.1 - 5.4)
Peak Power/ BM (W.kg.$^{-1}$)	**50 (6)**	**4.3** (3.9 - 5.1)	**3.5** (3.2 - 4.2)	**3.8** (3.5 - 4.6)	**4.9** (4.5 – 6.0)	**4.3** (4.0 - 5.2)
Mean Eccentric Concentric Power Time (W.s.$^{-1}$)	**2031 (491)**	**7.4** (6.8 - 8.9)	**8.7** (8.0 - 10.5)	**7.8** (7.2 - 9.4)	**10.3** (9.5 – 12.6)	**7.5** (6.9 – 9.0)
Peak Landing Power (W)	**23638 (6272)**	**12.5** (11.6 - 15.1)	**13.6** (12.6 - 16.5)	**10.3** (9.5 - 12.4)	**14.5** (13.3 - 17.6)	**12.7** (11.7 - 15.3)
Eccentric Peak Velocity (m.s.$^{-1}$)	**1.6 (0.2)**	**4.9** (4.5 - 5.9)	**6.2** (5.7 - 7.5)	**4.3** (4.0 - 5.3)	**6.0** (5.5 - 7.3)	**4.9** (4.5 – 6.0)
Concentric Peak Velocity (m.s.$^{-1}$)	**2.8 (0.2)**	**3.1** (2.9 - 3.8)	**2.4** (2.2 - 2.9)	**2.7** (2.5 - 3.3)	**3.5** (3.2 - 4.3)	**3.2** (2.9 - 3.9)
Velocity at Peak Power (m.s.$^{-1}$)	**2.5 (0.3)**	**3.2** (3.0 - 3.9)	**2.4** (2.2 - 3)	**2.8** (2.6 - 3.4)	**11.8** (10.9 - 14.3)	**3.3** (3.1 – 4.0)
Vertical Velocity at Takeoff (m.s.$^{-1}$)	**2.6 (0.2)**	**3.4** (3.1 - 4.1)	**2.6** (2.4 - 3.1)	**2.9** (2.7 - 3.6)	**3.7** (3.4 - 4.5)	**3.4** (3.2 - 4.1)
Peak Landing Velocity (m.s^{-1})	**1 (0.2)**	**16.9** (15.5 - 20.3)	**11.9** (10.9 - 14.4)	**19.3** (17.8 - 23.4)	**17.9** (16.5 - 21.8)	**16.2** (15.0 - 19.7)
Eccentric Braking RFD 100ms (N.s^{-1})	**4407 (2111)**	**32.0** (29.5 - 38.5)	**38.6** (35.6 - 46.7)	**44.6** (41.0 - 53.9)	**35.4** (32.6 – 43.0)	**32.0** (29.5 - 38.8)
Eccentric Braking RFD 100ms/ BM (N.s.kg^{-1})	**43 (20.9)**	**31.9** (29.4 - 38.4)	**38.5** (35.4 - 46.5)	**44.5** (41.0 - 53.9)	**34.9** (32.2 - 42.5)	**31.9** (29.4 - 38.6)
Eccentric Braking RFD (N.s^{-1})	**7375 (2293)**	**9.7** (8.9 - 11.6)	**10.3** (9.5 - 12.5)	**9.2** (8.5 - 11.2)	**13.6** (12.5 - 16.5)	**9.8** (9.0 - 11.9)
Eccentric Braking RFD/ BM (N.s.kg^{-1})	**72 (20)**	**9.4** (8.7 - 11.3)	**10.5** (9.6 - 12.7)	**9.0** (8.3 - 10.9)	**13.5** (12.4 - 16.4)	**9.5** (8.8 - 11.5)
Eccentric Deceleration RFD (N.s^{-1})	**8683 (3434)**	**12.1** (11.1 - 14.6)	**11.4** (10.5 - 13.8)	**11.6** (10.7 - 14)	**16.6** (15.3 - 20.1)	**12.1** (11.2 - 14.7)
Eccentric Deceleration RFD/ BM (N.s.kg^{-1})	**84 (29)**	**11.8** (10.9 - 14.3)	**11.5** (10.6 - 13.9)	**11.3** (10.4 - 13.7)	**16.8** (15.4 - 20.4)	**11.9** (11.0 - 14.4)

Variables	Mean (±SD)	Condition 1 Mon-Tue		Condition 2 Mon-Thu		Condition 3 Tue-Thu		Condition 4 Mon-Mon		Condition 5 Mon-Tue-Thu	
Concentric RPD 50ms ($W.s^{-1}$)	**32389 (9656)**	**8.3**	(7.7 - 10.1)	**8.8**	(8.1 - 10.6)	**9.1**	(8.3 - 11)	**11.0**	(10.1 - 13.3)	**8.4**	(7.7 - 10.1)
Concentric RPD 50ms/BM ($W.s.kg^{-1}$)	**314 (79)**	**8.1**	(7.5 - 9.8)	**8.9**	(8.2 - 10.7)	**8.9**	(8.2 - 10.7)	**11.0**	(10.1 - 13.4)	**8.2**	(7.5 - 9.9)
Concentric RPD 100ms ($W.s^{-1}$)	**26921 (8288)**	**7.0**	(6.4 - 8.4)	**7.9**	(7.2 - 9.5)	**7.6**	(7.0 - 9.2)	**9.4**	(8.7 - 11.4)	**7.0**	(6.5 - 8.5)
Concentric RPD 100ms/BM ($W.s.kg^{-1}$)	**261 (66)**	**6.8**	(6.3 - 8.2)	**7.9**	(7.3 - 9.6)	**7.5**	(6.9 - 9.1)	**9.5**	(8.7 - 11.5)	**6.8**	(6.3 - 8.3)
Concentric RPD ($W.s^{-1}$)	**23659 (6535)**	**5.5**	(5.0 - 6.6)	**5.3**	(4.8 - 6.4)	**4.9**	(4.6 – 6.0)	**6.9**	(6.4 - 8.4)	**5.6**	(5.2 - 6.8)
Concentric RPD/BM ($W.s.kg^{-1}$)	**230 (50)**	**5.3**	(4.9 - 6.4)	**5.4**	(5 - 6.6)	**4.9**	(4.5 - 5.9)	**7.1**	(6.5 - 8.6)	**5.5**	(5.0 - 6.7)
Concentric RFD 50ms ($N.s^{-1}$)	**-4360 (2244)**	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA
Concentric RFD 100ms ($N.s^{-1}$)	**-4352 (2048)**	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA
Concentric RFD 200ms ($N.s^{-1}$)	**-3175 (3104)**	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA
Concentric RFD ($N.s^{-1}$)	**372 (495)**	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA
Concentric RFD/BM ($N.s.kg^{-1}$)	**4 (5)**	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA
Landing RFD 50ms ($N.s^{-1}$)	**40919 (26154)**	**17.2**	(15.9 - 20.8)	**24.3**	(22.4 - 29.4)	**19.1**	(17.6 - 23.1)	**21.8**	(20.1 - 26.5)	**17.0**	(15.6 - 20.5)
Landing RFD ($N.s^{-1}$)	**539272 (240965)**	**28.0**	(25.8 - 33.8)	**28.9**	(26.6 - 35)	**19.8**	(18.2 - 23.9)	**30.2**	(27.8 - 36.7)	**28.5**	(26.2 - 34.5)
Jump Height (FT) Relative Landing RFD ($N.s.cm^{-1}$)	**12105 (5367)**	**27.7**	(25.5 - 33.4)	**29.0**	(26.7 - 35.1)	**19.4**	(17.8 - 23.4)	**30.3**	(27.9 - 36.8)	**28.1**	(25.9 – 34.0)

Appendix 2: Inter-day absolute reliability (CV) and 95% confidence intervals of countermovement jump variables using $\underline{Best_{JH}}$

Variables	Mean (±SD)	Condition 1 Mon-Tue		Condition 2 Mon-Thu		Condition 3 Tue-Thu		Condition 4 Mon-Mon		Condition 5 Mon-Tue-Thu	
Body Weight (kg)	**102.8 (12)**	**0.7**	(0.7 - 0.9)	**0.9**	(0.8 - 1.1)	**0.9**	(0.8 - 1.1)	**1.1**	(1.0 - 1.3)	**0.7**	(0.7 - 0.9)
Countermovement Depth (cm)	**44 (7)**	**7.6**	(7.0 - 9.2)	**5.9**	(5.4 - 7.1)	**5.6**	(5.2 - 6.8)	**6.4**	(5.9 - 7.8)	**7.7**	(7.1 - 9.3)
Jump Height - Flight Time (cm)	**45 (6)**	**2.7**	(2.5 - 3.3)	**3.0**	(2.8 - 3.7)	**2.6**	(2.4 - 3.1)	**3.7**	(3.4 - 4.6)	**2.8**	(2.6 - 3.4)
Jump Height - Impulse Momentum (cm)	**36 (6)**	**9.6**	(8.8 - 11.5)	**6.7**	(6.1 - 8.1)	**7.7**	(7.1 - 9.4)	**9.7**	(8.9 - 11.8)	**9.5**	(8.7 - 11.5)
Lower Limb Stiffness ($N.m^{-1}$)	**5706 (1616)**	**9.8**	(9.0 - 11.8)	**7.7**	(7.1 - 9.3)	**9.7**	(8.9 - 11.7)	**12.4**	(11.5 - 15.1)	**9.9**	(9.2 - 12)
CMJ Stiffness ($N.m^{-1}$)	**6053 (1558)**	**8.7**	(8.0 - 10.5)	**6.3**	(5.8 - 7.6)	**7.9**	(7.2 - 9.5)	**9.2**	(8.5 - 11.2)	**8.7**	(8.1 - 10.6)
Total Work (J)	**1268 (183)**	**4.3**	(4.0 - 5.2)	**3.3**	(3.0 – 4.0)	**4.2**	(3.9 - 5.1)	**3.9**	(3.6 - 4.7)	**4.3**	(3.9 - 5.2)
RSI modified ($m.s.^{-1}$)	**0.58 (0.09)**	**6.0**	(5.5 - 7.2)	**5.6**	(5.2 - 6.8)	**5.4**	(4.9 - 6.5)	**8.6**	(8.0 - 10.5)	**6.1**	(5.6 - 7.3)
Flight Time/ Contraction Time Ratio	**0.78 (0.10)**	**4.8**	(4.5 - 5.8)	**4.6**	(4.2 - 5.5)	**4.5**	(4.2 - 5.5)	**7.3**	(6.7 - 8.8)	**4.9**	(4.5 - 5.9)
Eccentric/ Concentric Duration (%)	**183 (20)**	**6.6**	(6.1 – 8.0)	**6.1**	(5.6 - 7.4)	**5.1**	(4.7 - 6.2)	**7.3**	(6.7 - 8.9)	**6.7**	(6.2 - 8.1)
Eccentric/ Concentric Mean Force (%)	**51 (3.4)**	**2.4**	(2.2 - 2.9)	**1.8**	(1.7 - 2.2)	**2.3**	(2.1 - 2.8)	**3.2**	(3.0 - 3.9)	**2.4**	(2.2 - 2.9)
Concentric Impulse 100ms/ Concentric Impulse Ratio	**0.49 (0.08)**	**5.1**	(4.7 - 6.1)	**5.3**	(4.9 - 6.4)	**6.3**	(5.8 - 7.7)	**4.3**	(4.0 - 5.3)	**5.1**	(4.7 - 6.2)
Eccentric Peak Power/ Concentric Peak Power Ratio	**0.50 (0.13)**	**15.8**	(14.5 – 19.0)	**13.9**	(12.8 - 16.9)	**12.6**	(11.6 - 15.2)	**15.5**	(14.2 - 18.8)	**15.8**	(14.5 - 19.1)
P2 Concentric Impulse/ P1 Concentric Impulse Ratio	**0.60 (0.12)**	**8.0**	(7.4 - 9.6)	**9.6**	(8.8 - 11.6)	**11.5**	(10.6 - 13.9)	**6.8**	(6.3 - 8.3)	**8.1**	(7.5 - 9.8)
Time to Braking Phase (s)	**0.18 (0.05)**	**16.3**	(15.0 - 19.6)	**15.6**	(14.4 - 18.9)	**15.2**	(14.0 - 18.4)	**21.4**	(19.7 - 26)	**16.5**	(15.2 - 19.9)
Eccentric Duration (ms)	**513 (85)**	**6.0**	(5.5 - 7.2)	**5.7**	(5.3 - 6.9)	**5.4**	(4.9 - 6.5)	**8.5**	(7.8 - 10.4)	**6.0**	(5.5 - 7.3)
Braking Phase Duration (s)	**0.33(0.05)**	**6.8**	(6.3 - 8.2)	**8.1**	(7.4 - 9.8)	**6.7**	(6.2 - 8.1)	**9.4**	(8.6 - 11.4)	**6.9**	(6.3 - 8.3)
Eccentric Acceleration Phase Duration (s)	**0.33 (0.07)**	**7.9**	(7.3 - 9.6)	**7.9**	(7.3 - 9.6)	**7.3**	(6.7 - 8.8)	**10.5**	(9.6 - 12.7)	**8.0**	(7.3 - 9.7)
Eccentric Deceleration Phase Duration (s)	**0.19 (0.03)**	**8.2**	(7.5 - 9.8)	**5.6**	(5.2 - 6.8)	**8.1**	(7.5 - 9.9)	**11.0**	(10.1 - 13.3)	**8.3**	(7.6 – 10.0)
Concentric Duration (ms)	**280 (33)**	**3.9**	(3.6 - 4.7)	**3.3**	(3.0 - 3.9)	**3.0**	(2.8 - 3.6)	**3.5**	(3.2 - 4.3)	**4.0**	(3.6 - 4.8)
Contraction Time (ms)	**793 (111)**	**4.3**	(4.0 - 5.2)	**4.1**	(3.8 – 5.0)	**4.0**	(3.6 - 4.8)	**6.3**	(5.8 - 7.7)	**4.3**	(4.0 - 5.2)
Concentric Time to Peak Force (ms)	**29 (46)**	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA
Movement Start to Peak Force (s)	**0.52 (0.10)**	**13.7**	(12.6 - 16.5)	**10.4**	(9.6 - 12.6)	**11.9**	(11.0 - 14.4)	**9.9**	(9.2 - 12.1)	**13.9**	(12.8 - 16.8)

Variables	Mean (±SD)	Condition 1 Mon-Tue	Condition 2 Mon-Thu	Condition 3 Tue-Thu	Condition 4 Mon-Mon	Condition 5 Mon-Tue-Thu
Movement Start to Peak Power (s)	**0.73 (0.11)**	**4.6** (4.3 - 5.6)	**4.4** (4.0 - 5.3)	**4.3** (3.9 - 5.2)	**6.8** (6.3 - 8.3)	**4.7** (4.3 - 5.7)
Flight Time (ms)	**607 (42)**	**1.4** (1.3 - 1.6)	**1.5** (1.4 - 1.8)	**1.3** (1.2 - 1.5)	**1.9** (1.7 - 2.3)	**1.4** (1.3 - 1.7)
Minimum Eccentric Force (N)	**141 (148)**	**107.3** (98.7– 131.0)	**69.9** (64.3 - 85.3)	**97.4** (89.5-119.5)	**90.7** (83.4-111.3)	**99.9** (91.8-122.6)
Eccentric Mean Force (N)	**1011 (118)**	**0.8** (0.7 - 0.9)	**0.9** (0.8 - 1.1)	**0.9** (0.8 - 1.1)	**1.1** (1.0 - 1.3)	**0.8** (0.7 - 0.9)
Eccentric Mean Braking Force (N)	**1276 (163)**	**3.9** (3.6 - 4.7)	**4.8** (4.4 - 5.7)	**4.7** (4.3 - 5.7)	**4.7** (4.3 - 5.7)	**3.9** (3.6 - 4.8)
Eccentric Mean Deceleration Force (N)	**1954 (336)**	**5.9** (5.4 - 7.1)	**4.7** (4.3 - 5.7)	**5.5** (5.1 - 6.7)	**7.4** (6.9 - 9.1)	**5.9** (5.5 - 7.2)
Eccentric Peak Force (N)	**2582 (405)**	**5.4** (5.0 - 6.5)	**5.2** (4.7 - 6.2)	**6.1** (5.6 - 7.4)	**7.2** (6.6 - 8.7)	**5.5** (5.1 - 6.6)
Eccentric Peak Force/ BM ($N.kg^{-1}$)	**25 (3)**	**5.2** (4.8 - 6.3)	**5.2** (4.8 - 6.3)	**5.9** (5.4 - 7.2)	**7.2** (6.6 - 8.7)	**5.3** (4.9 - 6.4)
Force at Zero Velocity (N)	**2548 (402)**	**5.1** (4.7 - 6.2)	**4.7** (4.3 - 5.7)	**6.0** (5.5 - 7.2)	**6.3** (5.8 - 7.7)	**5.2** (4.8 - 6.3)
Concentric Mean Force (N)	**1994 (277)**	**2.6** (2.4 - 3.2)	**1.9** (1.7 - 2.3)	**2.4** (2.2 – 3.0)	**3.2** (2.9 - 3.8)	**2.7** (2.5 - 3.2)
Concentric Mean Force/ BM ($N.kg^{-1}$)	**19 (1)**	**2.4** (2.2 - 2.9)	**1.9** (1.8 - 2.3)	**2.2** (2.0 - 2.7)	**3.3** (3.0 – 4.0)	**2.4** (2.2 – 3.0)
Concentric Peak Force (N)	**2567 (396)**	**3.7** (3.4 - 4.4)	**3.9** (3.6 - 4.7)	**5.3** (4.9 - 6.4)	**6.3** (5.8 - 7.6)	**3.7** (3.4 - 4.5)
Concentric Peak Force/ BM ($N.kg^{-1}$)	**25 (2)**	**3.6** (3.3 - 4.3)	**4.0** (3.7 - 4.9)	**5.0** (4.6 - 6.1)	**6.3** (5.8 - 7.7)	**3.6** (3.4 - 4.4)
Force at Peak Power (N)	**2058 (288)**	**3.4** (3.1 – 4.0)	**3.8** (3.5 - 4.6)	**3.0** (2.7 - 3.6)	**4.7** (4.3 - 5.7)	**3.4** (3.1 - 4.1)
Peak Net Takeoff Force/ BM ($N.kg^{-1}$)	**15 (2)**	**7.2** (6.6 - 8.7)	**8.0** (7.4 - 9.7)	**9.2** (8.4 - 11.1)	**12.2** (11.2 - 14.8)	**7.3** (6.7 - 8.9)
Peak Landing Force (N)	**8539 (2349)**	**20.4** (18.8 - 24.6)	**21.5** (19.8 – 26.0)	**15.8** (14.6 - 19.2)	**21.8** (20.1 - 26.5)	**19.6** (18.1 - 23.8)
Peak Landing Force/ BM (N)	**84 (23)**	**20.1** (18.5 - 24.2)	**21.5** (19.8 – 26.0)	**15.8** (14.6 - 19.1)	**21.7** (20.0 - 26.4)	**19.2** (17.7 - 23.3)
Landing Net Peak Force/ BM ($N.kg^{-1}$)	**74 (23)**	**23.2** (21.3 - 27.9)	**25.0** (23.1 - 30.3)	**18.0** (16.6 - 21.8)	**25.3** (23.3 - 30.7)	**22.3** (20.6 – 27.0)
Jump Height (FT) Relative Peak Landing Force ($N.cm^{-1}$)	**191 (56)**	**19.9** (18.4 – 24.0)	**20.8** (19.1 - 25.1)	**15.2** (14.0 - 18.3)	**21.6** (19.9 - 26.3)	**19.1** (17.6 - 23.1)
Eccentric Unloading Impulse (Ns)	**169 (28)**	**7.6** (7.0 - 9.2)	**7.4** (6.8 - 8.9)	**6.1** (5.6 - 7.3)	**8.6** (8.0 - 10.5)	**7.7** (7.1 - 9.3)
Eccentric Braking Impulse (Ns)	**84.9 (18.4)**	**17.0** (15.7 - 20.5)	**17.3** (15.9 - 20.9)	**16.2** (14.9 - 19.6)	**17.8** (16.4 - 21.6)	**17.2** (15.8 - 20.8)
Eccentric Deceleration Impulse (Ns)	**169 (28)**	**7.5** (6.9 - 9)	**7.3** (6.7 - 8.8)	**5.9** (5.4 - 7.1)	**8.5** (7.8 - 10.4)	**7.6** (7.0 - 9.2)
Concentric Impulse 50ms (Ns)	**72.4 (15.2)**	**7.6** (7.0 - 9.2)	**7.0** (6.4 - 8.4)	**8.8** (8.1 - 10.7)	**8.6** (7.9 - 10.5)	**7.7** (7.1 - 9.3)
Concentric Impulse 100ms (Ns)	**133 (28)**	**6.6** (6.1 - 7.9)	**5.8** (5.4 - 7.1)	**7.5** (6.9 - 9.1)	**7.4** (6.8 – 9.0)	**6.7** (6.1 - 8.1)

Variables	Mean (±SD)	Condition 1 Mon-Tue	Condition 2 Mon-Thu	Condition 3 Tue-Thu	Condition 4 Mon-Mon	Condition 5 Mon-Tue-Thu
Concentric Impulse (Ns)	**273 (33)**	**4.8** (4.4 - 5.7)	**3.0** (2.8 - 3.6)	**4.1** (3.8 – 5.0)	**4.4** (4.1 - 5.4)	**4.7** (4.3 - 5.7)
P1 Concentric Impulse (Ns)	**172 (24)**	**5.8** (5.3 – 7.0)	**4.6** (4.3 - 5.6)	**5.6** (5.2 - 6.8)	**5.4** (5.0 - 6.6)	**5.8** (5.3 – 7.0)
P2 Concentric Impulse (Ns)	**101 (18)**	**6.8** (6.3 - 8.2)	**6.9** (6.4 - 8.4)	**8.8** (8.1 - 10.7)	**5.7** (5.3 – 7.0)	**6.9** (6.3 - 8.3)
Landing Impulse (Ns)	**58 (25.5)**	**30.7** (28.3 - 36.9)	**28.9** (26.6 – 35.0)	**27.2** (25.1 - 33)	**37.5** (34.5 - 45.6)	**31.0** (28.5 - 37.5)
Eccentric Mean Power (W)	**873 (142)**	**8.0** (7.4 - 9.7)	**7.7** (7.1 - 9.3)	**6.2** (5.7 - 7.5)	**10.0** (9.2 - 12.1)	**8.0** (7.4 - 9.7)
Eccentric Mean Power / BM (W.kg.$^{-1}$)	**9 (1)**	**7.9** (7.3 - 9.5)	**7.5** (6.9 - 9.1)	**5.9** (5.5 - 7.2)	**9.6** (8.8 - 11.6)	**7.8** (7.2 - 9.5)
Eccentric Peak Power (W)	**2542 (636)**	**13.4** (12.4 - 16.2)	**12.3** (11.3 - 14.9)	**11.4** (10.5 - 13.8)	**16.5** (15.2 - 20.1)	**13.5** (12.5 - 16.4)
Eccentric Peak Power BM (W.kg.$^{-1}$)	**25 (5)**	**13.1** (12.1 - 15.8)	**12.2** (11.2 - 14.7)	**11.2** (10.4 - 13.6)	**16.3** (15.0 - 19.8)	**13.2** (12.2 – 16.0)
Concentric Mean Power (W)	**2942 (455)**	**6.6** (6.0 - 7.9)	**4.5** (4.1 - 5.4)	**5.6** (5.1 - 6.7)	**7.5** (6.9 - 9.1)	**6.5** (6.0 - 7.9)
Concentric Mean Power/ BM (W.kg.$^{-1}$)	**29 (3.3)**	**6.4** (5.9 - 7.7)	**4.7** (4.3 - 5.7)	**5.4** (5.0 - 6.5)	**7.7** (7.1 - 9.4)	**6.4** (5.9 - 7.7)
Peak Power (W)	**5150 (746)**	**6.1** (5.7 - 7.4)	**4.4** (4.1 - 5.4)	**5.0** (4.6 - 6.1)	**6.6** (6.1 – 8.0)	**6.1** (5.7 - 7.4)
Peak Power/ BM (W.kg.$^{-1}$)	**50 (6)**	**6.0** (5.5 - 7.2)	**4.7** (4.3 - 5.7)	**4.9** (4.5 - 5.9)	**7.0** (6.4 - 8.5)	**6.0** (5.5 - 7.2)
Mean Eccentric Concentric Power Time (W.s.$^{-1}$)	**2085 (488)**	**8.9** (8.2 - 10.7)	**8.7** (8.0 - 10.5)	**9.0** (8.3 - 10.9)	**14.0** (12.9 - 17)	**9.0** (8.3 - 10.9)
Peak Landing Power (W)	**25140 (7164)**	**22.1** (20.4 - 26.7)	**22.7** (20.9 - 27.5)	**15.9** (14.6 - 19.2)	**22.3** (20.6 - 27.1)	**21.3** (19.6 - 25.8)
Eccentric Peak Velocity (m.s.$^{-1}$)	**1.7 (0.2)**	**7.4** (6.8 - 8.9)	**7.1** (6.5 - 8.6)	**5.8** (5.4 – 7.0)	**8.3** (7.6 – 10.0)	**7.4** (6.9 – 9.0)
Concentric Peak Velocity (m.s.$^{-1}$)	**2.8 (0.2)**	**4.4** (4.0 - 5.2)	**3.1** (2.8 - 3.7)	**3.4** (3.1 - 4.1)	**4.5** (4.1 - 5.4)	**4.3** (4.0 - 5.2)
Velocity at Peak Power (m.s.$^{-1}$)	**2.5 (0.34)**	**4.4** (4.0 - 5.3)	**3.1** (2.9 - 3.8)	**3.5** (3.2 - 4.2)	**4.4** (4.1 - 5.4)	**4.4** (4.0 - 5.3)
Vertical Velocity at Takeoff (m.s.$^{-1}$)	**2.7 (0.21)**	**4.7** (4.3 - 5.6)	**3.3** (3.0 – 4.0)	**3.8** (3.5 - 4.6)	**4.7** (4.4 - 5.8)	**4.6** (4.3 - 5.6)
Peak Landing Velocity (m.s^{-1})	**1.01 (0.23)**	**21.9** (20.2 - 26.4)	**17.1** (15.7 - 20.7)	**19.3** (17.8 - 23.4)	**27.3** (25.1 - 33.2)	**17.6** (16.3 - 21.3)
Eccentric Braking RFD 100ms (N.s^{-1})	**4628 (2830)**	**63.6** (58.7 - 76.7)	**66.2** (61.0 - 80.1)	**51.5** (47.5 - 62.4)	**82.0** (75.5 - 99.6)	**64.1** (59.0 - 77.6)
Eccentric Braking RFD 100ms/ BM (N.s.kg^{-1})	**46 (28)**	**62.4** (57.5 - 75.2)	**65.3** (60.1 – 79.0)	**51.7** (47.6 - 62.6)	**80.6** (74.2 - 98)	**62.8** (57.8 - 76)
Eccentric Braking RFD (N.s^{-1})	**7565 (2379)**	**12.1** (11.2 - 14.6)	**13.8** (12.8 - 16.8)	**13.3** (12.3 - 16.1)	**18.1** (16.7 - 22)	**12.3** (11.3 - 14.9)
Eccentric Braking RFD/ BM (N.s.kg^{-1})	**74 (21)**	**11.7** (10.8 - 14.1)	**13.8** (12.7 - 16.7)	**13.0** (12.0 - 15.8)	**17.9** (16.5 - 21.8)	**11.9** (10.9 - 14.4)
Eccentric Deceleration RFD (N.s^{-1})	**8848 (3380)**	**16.8** (15.5 - 20.3)	**13.6** (12.6 - 16.5)	**17.5** (16.1 - 21.1)	**21.6** (19.9 - 26.3)	**17.1** (15.8 - 20.7)
Eccentric Deceleration RFD/ BM (N.s.kg^{-1})	**86 (29)**	**16.7** (15.4 - 20.1)	**13.9** (12.8 - 16.8)	**17.2** (15.8 - 20.8)	**22.0** (20.2 - 26.7)	**17.0** (15.6 - 20.5)

Variables	Mean (±SD)	Condition 1 Mon-Tue		Condition 2 Mon-Thu		Condition 3 Tue-Thu		Condition 4 Mon-Mon		Condition 5 Mon-Tue-Thu	
Concentric RPD 50ms ($W.s^{-1}$)	**33044 (9725)**	**11.2**	(10.3 - 13.5)	**10.6**	(9.7 - 12.8)	**12.3**	(11.4 - 14.9)	**13.2**	(12.2 - 16.1)	**11.4**	(10.5 - 13.7)
Concentric RPD 50ms/BM ($W.s.kg^{-1}$)	**321 (80)**	**11.1**	(10.2 - 13.3)	**10.7**	(9.9 – 13.0)	**12.2**	(11.2 - 14.7)	**13.4**	(12.4 - 16.3)	**11.2**	(10.3 - 13.6)
Concentric RPD 100ms ($W.s^{-1}$)	**27580 (8407)**	**9.4**	(8.7 - 11.4)	**8.3**	(7.6 – 10.0)	**9.5**	(8.8 - 11.5)	**10.9**	(10 - 13.2)	**9.6**	(8.8 - 11.6)
Concentric RPD 100ms/BM ($W.s.kg^{-1}$)	**267 (67)**	**9.2**	(8.5 - 11.1)	**8.4**	(7.7 - 10.1)	**9.3**	(8.6 - 11.3)	**11.1**	(10.2 - 13.4)	**9.4**	(8.6 - 11.3)
Concentric RPD ($W.s^{-1}$)	**24190 (6726)**	**7.6**	(7.1 - 9.2)	**6.0**	(5.5 - 7.3)	**5.8**	(5.3 – 7.0)	**9.8**	(9.0 – 12.0)	**7.9**	(7.2 - 9.6)
Concentric RPD/BM ($W.s.kg^{-1}$)	**235 (51)**	**7.5**	(6.9 – 9.0)	**6.2**	(5.7 - 7.5)	**5.6**	(5.1 - 6.8)	**10.1**	(9.3 - 12.4)	**7.7**	(7.1 - 9.3)
Concentric RFD 50ms ($N.s^{-1}$)	**-4251 (2142)**	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA
Concentric RFD 100ms ($N.s^{-1}$)	**-4277 (1964)**	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA
Concentric RFD 200ms ($N.s^{-1}$)	**-3298 (3611)**	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA
Concentric RFD ($N.s^{-1}$)	**322 (525)**	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA
Concentric RFD/BM ($N.s.kg^{-1}$)	**3 (5)**	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA	**NA**	NA
Landing RFD 50ms ($N.s^{-1}$)	**38353 (25471)**	**32.2**	(29.7 - 38.8)	**29.7**	(27.4 – 36.0)	**26.9**	(24.7 - 32.5)	**33.5**	(30.8 - 40.7)	**31.9**	(29.4 - 38.6)
Landing RFD ($N.s^{-1}$)	**604117 (273813)**	**46.5**	(42.9 - 56)	**41.8**	(38.5 - 50.6)	**34.6**	(31.9 - 41.9)	**45.8**	(42.1 - 55.6)	**47.0**	(43.3 - 56.8)
Jump Height (FT) Relative Landing RFD ($N.s.cm^{-1}$)	**13265 (5796)**	**45.4**	(41.8 - 54.7)	**41.0**	(37.8 - 49.6)	**33.8**	(31.1 - 40.9)	**45.1**	(41.5 - 54.8)	**45.8**	(42.2 - 55.4)

Appendix 3. Inter-day relative reliability (ICC) and 95% confidence intervals of countermovement jump variables using Mean$_3$

Variables	Mean (±SD)	Condition 1 M-Tu		Condition 2 M-Th		Condition 3 Tu-Th		Condition 4 M-M		Condition 5 M-Tu-Th	
Body Weight (kg)	**102.8 (12)**	**0.997**	(0.992-0.999)	**0.997**	(0.992-0.998)	**0.995**	(0.964-0.998)	**0.995**	(0.991-0.998)	**0.997**	(0.994-0.999)
Countermovement Depth (cm)	**44.3 (7)**	**0.95**	(0.90-0.98)	**0.97**	(0.93-0.98)	**0.97**	(0.92-0.98)	**0.96**	(0.92-0.98)	**0.97**	(0.95-0.99)
Jump Height - Flight Time (cm)	**44.5 (6)**	**0.97**	(0.92-0.99)	**0.98**	(0.96-0.99)	**0.98**	(0.93-0.99)	**0.96**	(0.88-0.98)	**0.98**	(0.97-0.99)
Jump Height - Impulse Momentum (cm)	**36 (6)**	**0.90**	(0.73-0.96)	**0.95**	(0.91-0.98)	**0.92**	(0.79-0.96)	**0.89**	(0.74-0.95)	**0.95**	(0.90-0.97)
Lower Limb Stiffness (N.m^{-1})	**5632 (1697)**	**0.95**	(0.91-0.98)	**0.98**	(0.96-0.99)	**0.96**	(0.92-0.98)	**0.97**	(0.94-0.99)	**0.98**	(0.96-0.99)
CMJ Stiffness (N.m^{-1})	**6035 (1637)**	**0.95**	(0.90-0.98)	**0.98**	(0.97-0.99)	**0.96**	(0.92-0.98)	**0.98**	(0.95-0.99)	**0.98**	(0.96-0.99)
Total Work (J)	**1265 (180)**	**0.96**	(0.82-0.99)	**0.98**	(0.97-0.99)	**0.95**	(0.67-0.98)	**0.97**	(0.93-0.98)	**0.98**	(0.93-0.99)
RSI modified (m.s.$^{-1}$)	**0.56 (0.09)**	**0.95**	(0.89-0.97)	**0.95**	(0.90-0.98)	**0.95**	(0.89-0.98)	**0.90**	(0.79-0.95)	**0.97**	(0.94-0.98)
Flight Time/ Contraction Time Ratio	**0.76 (0.10)**	**0.95**	(0.90-0.98)	**0.95**	(0.91-0.98)	**0.95**	(0.91-0.98)	**0.92**	(0.83-0.96)	**0.97**	(0.94-0.98)
Eccentric/ Concentric Duration (%)	**184 (19)**	**0.91**	(0.81-0.95)	**0.86**	(0.72-0.93)	**0.91**	(0.83-0.96)	**0.89**	(0.79-0.95)	**0.93**	(0.87-0.96)
Eccentric/ Concentric Mean Force (%)	**52 (3)**	**0.96**	(0.88-0.98)	**0.97**	(0.94-0.98)	**0.96**	(0.92-0.98)	**0.92**	(0.77-0.97)	**0.97**	(0.95-0.99)
Concentric Impulse 100ms/ Concentric Impulse Ratio	**0.48 (0.08)**	**0.96**	(0.91-0.98)	**0.96**	(0.93-0.98)	**0.96**	(0.92-0.98)	**0.97**	(0.94-0.98)	**0.97**	(0.95-0.99)
Eccentric Peak Power/ Concentric Peak Power Ratio	**0.45 (0.12)**	**0.91**	(0.82-0.95)	**0.90**	(0.81-0.95)	**0.91**	(0.80-0.96)	**0.92**	(0.83-0.96)	**0.94**	(0.89-0.97)
P2 Concentric Impulse/ P1 Concentric Impulse Ratio	**0.60 (0.12)**	**0.95**	(0.90-0.98)	**0.94**	(0.87-0.97)	**0.95**	(0.87-0.98)	**0.95**	(0.91-0.98)	**0.96**	(0.93-0.98)
Time to Braking Phase (s)	**0.18 (0.05)**	**0.92**	(0.84-0.96)	**0.82**	(0.64-0.91)	**0.88**	(0.76-0.94)	**0.89**	(0.79-0.95)	**0.91**	(0.85-0.95)
Eccentric Duration (ms)	**521 (84)**	**0.96**	(0.92-0.98)	**0.91**	(0.81-0.95)	**0.94**	(0.88-0.97)	**0.91**	(0.81-0.96)	**0.96**	(0.92-0.98)
Braking Phase Duration (s)	**0.34 (0.05)**	**0.94**	(0.87-0.97)	**0.94**	(0.87-0.97)	**0.96**	(0.91-0.98)	**0.89**	(0.78-0.95)	**0.96**	(0.93-0.98)
Eccentric Acceleration Phase Duration (s)	**0.33 (0.06)**	**0.94**	(0.88-0.97)	**0.85**	(0.71-0.93)	**0.90**	(0.80-0.95)	**0.90**	(0.79-0.95)	**0.93**	(0.88-0.97)
Eccentric Deceleration Phase Duration (s)	**0.19 (0.04)**	**0.94**	(0.77-0.98)	**0.96**	(0.92-0.98)	**0.95**	(0.86-0.98)	**0.91**	(0.81-0.95)	**0.96**	(0.93-0.98)
Concentric Duration (ms)	**283 (33)**	**0.97**	(0.93-0.98)	**0.97**	(0.95-0.99)	**0.97**	(0.95-0.99)	**0.96**	(0.92-0.98)	**0.98**	(0.96-0.99)
Contraction Time (ms)	**804 (111)**	**0.97**	(0.93-0.98)	**0.93**	(0.87-0.97)	**0.95**	(0.91-0.98)	**0.93**	(0.85-0.96)	**0.97**	(0.94-0.98)
Concentric Time to Peak Force (ms)	**29 (44)**	**0.79**	(0.59-0.89)	**0.63**	(0.24-0.81)	**0.74**	(0.49-0.87)	**0.76**	(0.52-0.88)	**0.80**	(0.64-0.89)
Movement Start to Peak Force (s)	**0.53 (0.10)**	**0.86**	(0.73-0.93)	**0.80**	(0.61-0.9)	**0.87**	(0.74-0.94)	**0.84**	(0.67-0.92)	**0.89**	(0.81-0.94)

Variables	Mean (±SD)	Condition 1 M-Tu		Condition 2 M-Th		Condition 3 Tu-Th		Condition 4 M-M		Condition 5 M-Tu-Th	
Movement Start to Peak Power (s)	**0.74 (0.11)**	**0.97**	(0.93-0.98)	**0.93**	(0.87-0.97)	**0.96**	(0.91-0.98)	**0.93**	(0.85-0.96)	**0.97**	(0.94-0.98)
Flight Time (ms)	**601 (43)**	**0.98**	(0.92-0.99)	**0.98**	(0.96-0.99)	**0.98**	(0.93-0.99)	**0.96**	(0.88-0.98)	**0.98**	(0.97-0.99)
Minimum Eccentric Force (N)	**161 (137)**	**0.97**	(0.94-0.98)	**0.90**	(0.81-0.95)	**0.95**	(0.90-0.98)	**0.93**	(0.85-0.96)	**0.96**	(0.93-0.98)
Eccentric Mean Force (N)	**1011 (118)**	**0.997**	(0.99-1.00)	**0.996**	(0.99-1.00)	**0.995**	(0.96-1.00)	**0.995**	(0.99-1.00)	**0.997**	(0.99-1.00)
Eccentric Mean Braking Force (N)	**1269 (155)**	**0.96**	(0.91-0.98)	**0.96**	(0.92-0.98)	**0.96**	(0.89-0.98)	**0.95**	(0.90-0.97)	**0.97**	(0.95-0.99)
Eccentric Mean Deceleration Force (N)	**1932 (337)**	**0.96**	(0.83-0.99)	**0.97**	(0.95-0.99)	**0.96**	(0.79-0.99)	**0.96**	(0.91-0.98)	**0.98**	(0.94-0.99)
Eccentric Peak Force (N)	**2566 (406)**	**0.94**	(0.56-0.98)	**0.97**	(0.93-0.98)	**0.94**	(0.65-0.98)	**0.94**	(0.88-0.97)	**0.97**	(0.90-0.99)
Eccentric Peak Force/ BM ($N.kg^{-1}$)	**25 (2.5)**	**0.88**	(0.33-0.96)	**0.92**	(0.84-0.96)	**0.90**	(0.56-0.96)	**0.88**	(0.75-0.94)	**0.93**	(0.82-0.97)
Force at Zero Velocity (N)	**2534 (404)**	**0.95**	(0.66-0.98)	**0.97**	(0.94-0.99)	**0.95**	(0.72-0.98)	**0.95**	(0.90-0.98)	**0.97**	(0.92-0.99)
Concentric Mean Force (N)	**1974 (272)**	**0.99**	(0.95-0.99)	**0.99**	(0.99-1.00)	**0.99**	(0.94-1.00)	**0.98**	(0.95-0.99)	**0.99**	(0.98-1.00)
Concentric Mean Force/ BM ($N.kg^{-1}$)	**19 (1.3)**	**0.96**	(0.89-0.98)	**0.97**	(0.94-0.98)	**0.97**	(0.93-0.98)	**0.92**	(0.77-0.97)	**0.98**	(0.95-0.99)
Concentric Peak Force (N)	**2555 (395)**	**0.96**	(0.60-0.99)	**0.98**	(0.96-0.99)	**0.95**	(0.77-0.98)	**0.96**	(0.92-0.98)	**0.97**	(0.92-0.99)
Concentric Peak Force/ BM ($N.kg^{-1}$)	**25 (2.3)**	**0.90**	(0.36-0.97)	**0.95**	(0.90-0.98)	**0.91**	(0.69-0.96)	**0.91**	(0.81-0.95)	**0.94**	(0.85-0.98)
Force at Peak Power (N)	**2042 (279)**	**0.99**	(0.97-0.99)	**0.98**	(0.96-0.99)	**0.98**	(0.94-0.99)	**0.98**	(0.96-0.99)	**0.99**	(0.98-0.99)
Peak Net Takeoff Force/ BM ($N.kg^{-1}$)	**15 (2.4)**	**0.88**	(0.16-0.96)	**0.94**	(0.87-0.97)	**0.90**	(0.61-0.96)	**0.89**	(0.77-0.95)	**0.93**	(0.81-0.97)
Peak Landing Force (N)	**8165 (2072)**	**0.90**	(0.79-0.95)	**0.87**	(0.75-0.94)	**0.90**	(0.81-0.95)	**0.89**	(0.75-0.95)	**0.92**	(0.86-0.96)
Peak Landing Force/ BM (N)	**80 (21)**	**0.89**	(0.78-0.94)	**0.86**	(0.73-0.93)	**0.91**	(0.82-0.96)	**0.87**	(0.71-0.94)	**0.92**	(0.86-0.96)
Landing Net Peak Force/ BM ($N.kg^{-1}$)	**70 (21)**	**0.89**	(0.78-0.94)	**0.86**	(0.73-0.93)	**0.91**	(0.82-0.95)	**0.87**	(0.72-0.94)	**0.92**	(0.86-0.96)
Jump Height (FT) Relative Peak Landing Force ($N.cm^{-1}$)	**187 (53)**	**0.92**	(0.85-0.96)	**0.89**	(0.79-0.95)	**0.94**	(0.88-0.97)	**0.92**	(0.83-0.96)	**0.94**	(0.90-0.97)
Eccentric Unloading Impulse (Ns)	**167 (27)**	**0.95**	(0.88-0.97)	**0.93**	(0.86-0.97)	**0.94**	(0.72-0.98)	**0.93**	(0.85-0.96)	**0.96**	(0.91-0.98)
Eccentric Braking Impulse (Ns)	**84 (16)**	**0.84**	(0.68-0.92)	**0.85**	(0.69-0.92)	**0.88**	(0.75-0.94)	**0.76**	(0.51-0.88)	**0.90**	(0.82-0.95)
Eccentric Deceleration Impulse (Ns)	**167 (27)**	**0.95**	(0.88-0.98)	**0.93**	(0.86-0.97)	**0.94**	(0.72-0.98)	**0.92**	(0.85-0.96)	**0.96**	(0.92-0.98)
Concentric Impulse 50ms (Ns)	**72 (15)**	**0.95**	(0.73-0.98)	**0.97**	(0.94-0.99)	**0.94**	(0.77-0.98)	**0.95**	(0.90-0.98)	**0.97**	(0.92-0.99)
Concentric Impulse 100ms (Ns)	**131 (28)**	**0.96**	(0.84-0.99)	**0.98**	(0.95-0.99)	**0.96**	(0.85-0.98)	**0.96**	(0.92-0.98)	**0.98**	(0.95-0.99)

Variables	Mean (±SD)	Condition 1 M-Tu	Condition 2 M-Th	Condition 3 Tu-Th	Condition 4 M-M	Condition 5 M-Tu-Th
Concentric Impulse (Ns)	**271 (33)**	**0.95** (0.84-0.98)	**0.98** (0.96-0.99)	**0.95** (0.81-0.98)	**0.95** (0.88-0.98)	**0.97** (0.94-0.99)
P1 Concentric Impulse (Ns)	**171 (25)**	**0.95** (0.78-0.98)	**0.97** (0.95-0.99)	**0.94** (0.69-0.98)	**0.95** (0.91-0.98)	**0.97** (0.92-0.99)
P2 Concentric Impulse (Ns)	**100 (17)**	**0.95** (0.91-0.98)	**0.96** (0.92-0.98)	**0.97** (0.93-0.98)	**0.95** (0.87-0.98)	**0.97** (0.95-0.99)
Landing Impulse (Ns)	**60 (25.4)**	**0.91** (0.83-0.96)	**0.84** (0.67-0.92)	**0.95** (0.91-0.98)	**0.76** (0.51-0.88)	**0.93** (0.88-0.96)
Eccentric Mean Power (W)	**862 (134)**	**0.94** (0.87-0.97)	**0.93** (0.85-0.96)	**0.93** (0.79-0.97)	**0.90** (0.80-0.95)	**0.95** (0.91-0.98)
Eccentric Mean Power / BM (W.kg.$^{-1}$)	**8.4 (1)**	**0.89** (0.78-0.94)	**0.88** (0.76-0.94)	**0.91** (0.77-0.96)	**0.87** (0.74-0.94)	**0.92** (0.87-0.96)
Eccentric Peak Power (W)	**2481 (613)**	**0.92** (0.80-0.97)	**0.93** (0.85-0.96)	**0.90** (0.66-0.96)	**0.92** (0.83-0.96)	**0.94** (0.88-0.97)
Eccentric Peak Power BM (W.kg.$^{-1}$)	**24 (5)**	**0.90** (0.75-0.95)	**0.90** (0.81-0.95)	**0.88** (0.62-0.95)	**0.90** (0.80-0.95)	**0.93** (0.86-0.96)
Concentric Mean Power (W)	**2896 (459)**	**0.94** (0.78-0.98)	**0.97** (0.94-0.99)	**0.95** (0.78-0.98)	**0.93** (0.82-0.97)	**0.97** (0.92-0.98)
Concentric Mean Power/ BM (W.kg.$^{-1}$)	**28 (3.3)**	**0.90** (0.68-0.96)	**0.94** (0.88-0.97)	**0.92** (0.76-0.97)	**0.87** (0.69-0.94)	**0.95** (0.89-0.97)
Peak Power (W)	**5088 (754)**	**0.94** (0.81-0.98)	**0.97** (0.95-0.99)	**0.95** (0.84-0.98)	**0.93** (0.78-0.97)	**0.97** (0.94-0.99)
Peak Power/ BM (W.kg.$^{-1}$)	**50 (6)**	**0.91** (0.74-0.96)	**0.95** (0.90-0.98)	**0.94** (0.84-0.97)	**0.89** (0.66-0.95)	**0.95** (0.91-0.98)
Mean Eccentric Concentric Power Time (W.s.$^{-1}$)	**2031 (491)**	**0.95** (0.89-0.97)	**0.96** (0.91-0.98)	**0.96** (0.90-0.98)	**0.91** (0.81-0.96)	**0.97** (0.94-0.98)
Peak Landing Power (W)	**23638 (6272)**	**0.90** (0.80-0.95)	**0.88** (0.76-0.94)	**0.91** (0.82-0.95)	**0.88** (0.75-0.94)	**0.93** (0.87-0.96)
Eccentric Peak Velocity (m.s.$^{-1}$)	**1.6 (0.2)**	**0.92** (0.82-0.96)	**0.89** (0.78-0.94)	**0.92** (0.72-0.97)	**0.89** (0.78-0.95)	**0.94** (0.88-0.97)
Concentric Peak Velocity (m.s.$^{-1}$)	**2.8 (0.2)**	**0.89** (0.70-0.95)	**0.95** (0.90-0.98)	**0.91** (0.74-0.96)	**0.88** (0.72-0.95)	**0.94** (0.88-0.97)
Velocity at Peak Power (m.s.$^{-1}$)	**2.5 (0.3)**	**0.89** (0.69-0.95)	**0.46** (-0.08-0.73)	**0.45** (-0.13-0.73)	**0.70** (0.39-0.85)	**0.61** (0.32-0.79)
Vertical Velocity at Takeoff (m.s.$^{-1}$)	**2.6 (0.2)**	**0.90** (0.74-0.95)	**0.95** (0.91-0.98)	**0.92** (0.79-0.96)	**0.89** (0.74-0.95)	**0.95** (0.9-0.97)
Peak Landing Velocity (m.s^{-1})	**1 (0.2)**	**0.88** (0.76-0.94)	**0.84** (0.67-0.92)	**0.84** (0.67-0.92)	**0.64** (0.27-0.82)	**0.90** (0.83-0.95)
Eccentric Braking RFD 100ms (N.s^{-1})	**4407 (2111)**	**0.85** (0.69-0.92)	**0.86** (0.73-0.93)	**0.86** (0.71-0.93)	**0.85** (0.68-0.93)	**0.90** (0.82-0.95)
Eccentric Braking RFD 100ms/ BM (N.s.kg^{-1})	**43 (20.9)**	**0.85** (0.69-0.92)	**0.88** (0.76-0.94)	**0.86** (0.72-0.93)	**0.86** (0.71-0.93)	**0.90** (0.83-0.95)
Eccentric Braking RFD (N.s^{-1})	**7375 (2293)**	**0.94** (0.86-0.98)	**0.96** (0.92-0.98)	**0.95** (0.88-0.98)	**0.94** (0.88-0.97)	**0.97** (0.94-0.98)
Eccentric Braking RFD/ BM (N.s.kg^{-1})	**72 (20)**	**0.93** (0.84-0.97)	**0.95** (0.90-0.98)	**0.95** (0.88-0.98)	**0.92** (0.84-0.96)	**0.96** (0.93-0.98)
Eccentric Deceleration RFD (N.s^{-1})	**8683 (3434)**	**0.94** (0.71-0.98)	**0.97** (0.94-0.99)	**0.95** (0.84-0.98)	**0.95** (0.90-0.97)	**0.97** (0.93-0.99)
Eccentric Deceleration RFD/ BM (N.s.kg^{-1})	**84 (29)**	**0.93** (0.66-0.98)	**0.96** (0.92-0.98)	**0.94** (0.82-0.97)	**0.93** (0.86-0.97)	**0.96** (0.91-0.98)

Variables	Mean (±SD)	Condition 1 M-Tu		Condition 2 M-Th		Condition 3 Tu-Th		Condition 4 M-M		Condition 5 M-Tu-Th	
Concentric RPD 50ms ($W.s^{-1}$)	**32389 (9656)**	**0.95**	(0.80-0.98)	**0.97**	(0.94-0.98)	**0.95**	(0.82-0.98)	**0.95**	(0.89-0.97)	**0.97**	(0.93-0.99)
Concentric RPD 50ms/BM ($W.s.kg^{-1}$)	**314 (79)**	**0.93**	(0.75-0.97)	**0.95**	(0.90-0.98)	**0.94**	(0.80-0.97)	**0.92**	(0.84-0.96)	**0.96**	(0.91-0.98)
Concentric RPD 100ms ($W.s^{-1}$)	**26921 (8288)**	**0.97**	(0.91-0.99)	**0.97**	(0.95-0.99)	**0.97**	(0.91-0.99)	**0.96**	(0.91-0.98)	**0.98**	(0.96-0.99)
Concentric RPD 100ms/BM ($W.s.kg^{-1}$)	**261 (66)**	**0.96**	(0.89-0.98)	**0.96**	(0.92-0.98)	**0.96**	(0.90-0.98)	**0.94**	(0.87-0.97)	**0.97**	(0.95-0.99)
Concentric RPD ($W.s^{-1}$)	**23659 (6535)**	**0.97**	(0.94-0.99)	**0.98**	(0.95-0.99)	**0.98**	(0.96-0.99)	**0.96**	(0.91-0.98)	**0.99**	(0.97-0.99)
Concentric RPD/BM ($W.s.kg^{-1}$)	**230 (50)**	**0.96**	(0.91-0.98)	**0.96**	(0.93-0.98)	**0.98**	(0.95-0.99)	**0.94**	(0.84-0.97)	**0.98**	(0.96-0.99)
Concentric RFD 50ms ($N.s^{-1}$)	**-4360 (2244)**	**0.83**	(0.33-0.94)	**0.87**	(0.73-0.93)	**0.88**	(0.58-0.95)	**0.83**	(0.65-0.91)	**0.90**	(0.77-0.95)
Concentric RFD 100ms ($N.s^{-1}$)	**-4352 (2048)**	**0.87**	(0.44-0.95)	**0.92**	(0.83-0.96)	**0.89**	(0.63-0.95)	**0.90**	(0.80-0.95)	**0.92**	(0.82-0.96)
Concentric RFD 200ms ($N.s^{-1}$)	**-3175 (3104)**	**0.96**	(0.92-0.98)	**0.96**	(0.93-0.98)	**0.97**	(0.94-0.99)	**0.96**	(0.91-0.98)	**0.98**	(0.96-0.99)
Concentric RFD ($N.s^{-1}$)	**372 (495)**	**0.30**	(-0.40-0.64)	**0.73**	(0.46-0.87)	**0.37**	(-0.26-0.68)	**0.76**	(0.52-0.88)	**0.52**	(0.16-0.75)
Concentric RFD/BM ($N.s.kg^{-1}$)	**4 (5)**	**0.28**	(-0.44-0.64)	**0.73**	(0.46-0.87)	**0.33**	(-0.34-0.66)	**0.74**	(0.47-0.87)	**0.51**	(0.13-0.74)
Landing RFD 50ms ($N.s^{-1}$)	**40919 (26154)**	**0.90**	(0.81-0.95)	**0.80**	(0.60-0.90)	**0.94**	(0.87-0.97)	**0.82**	(0.64-0.91)	**0.92**	(0.85-0.96)
Landing RFD ($N.s^{-1}$)	**539272 (240965)**	**0.83**	(0.67-0.92)	**0.84**	(0.68-0.92)	**0.88**	(0.76-0.94)	**0.86**	(0.72-0.93)	**0.89**	(0.81-0.94)
Jump Height (FT) Relative Landing RFD ($N.s.cm^{-1}$)	**12105 (5367)**	**0.85**	(0.69-0.92)	**0.84**	(0.68-0.92)	**0.90**	(0.81-0.95)	**0.87**	(0.73-0.93)	**0.90**	(0.83-0.95)

Appendix 4. Inter-day relative reliability (ICC) and 95% confidence intervals of countermovement jump variables using $\underline{Best_{JH}}$

Variables	Mean (±SD)	Condition 1 M-Tu		Condition 2 M-Th		Condition 3 Tu-Th		Condition 4 M-M		Condition 5 M-Tu-Th	
Body Weight (kg)	**102.8 (12)**	**0.997**	(0.992-0.999)	**0.997**	(0.992-0.998)	**0.995**	(0.964-0.998)	**0.995**	(0.991-0.998)	**0.997**	(0.994-0.999)
Countermovement Depth (cm)	**44.2 (6.6)**	**0.89**	(0.77-0.94)	**0.93**	(0.86-0.96)	**0.93**	(0.84-0.97)	**0.93**	(0.85-0.96)	**0.94**	(0.90-0.97)
Jump Height - Flight Time (cm)	**45.4 (6.3)**	**0.97**	(0.91-0.99)	**0.98**	(0.95-0.99)	**0.98**	(0.92-0.99)	**0.95**	(0.88-0.98)	**0.98**	(0.97-0.99)
Jump Height - Impulse Momentum (cm)	**36.4 (5.8)**	**0.85**	(0.70-0.93)	**0.93**	(0.86-0.97)	**0.89**	(0.79-0.95)	**0.84**	(0.63-0.92)	**0.93**	(0.87-0.96)
Lower Limb Stiffness ($N.m^{-1}$)	**5706 (1616)**	**0.93**	(0.87-0.97)	**0.96**	(0.93-0.98)	**0.94**	(0.88-0.97)	**0.93**	(0.86-0.97)	**0.96**	(0.93-0.98)
CMJ Stiffness ($N.m^{-1}$)	**6053 (1558)**	**0.93**	(0.87-0.97)	**0.97**	(0.93-0.98)	**0.95**	(0.90-0.98)	**0.95**	(0.89-0.97)	**0.97**	(0.94-0.98)
Total Work (J)	**1268 (183)**	**0.95**	(0.84-0.98)	**0.97**	(0.95-0.99)	**0.94**	(0.83-0.98)	**0.96**	(0.91-0.98)	**0.97**	(0.93-0.98)
RSI modified ($m.s.^{-1}$)	**0.582 (0.093)**	**0.93**	(0.85-0.97)	**0.95**	(0.90-0.98)	**0.94**	(0.84-0.97)	**0.87**	(0.70-0.94)	**0.96**	(0.93-0.98)
Flight Time/ Contraction Time Ratio	**0.779 (0.104)**	**0.94**	(0.87-0.97)	**0.96**	(0.91-0.98)	**0.94**	(0.87-0.97)	**0.87**	(0.73-0.94)	**0.96**	(0.93-0.98)
Eccentric/ Concentric Duration (%)	**183 (20)**	**0.84**	(0.68-0.92)	**0.85**	(0.69-0.92)	**0.90**	(0.79-0.95)	**0.78**	(0.56-0.89)	**0.90**	(0.83-0.95)
Eccentric/ Concentric Mean Force (%)	**51 (3.4)**	**0.93**	(0.85-0.97)	**0.96**	(0.93-0.98)	**0.94**	(0.89-0.97)	**0.86**	(0.67-0.94)	**0.96**	(0.93-0.98)
Concentric Impulse 100ms/ Concentric Impulse Ratio	**0.485 (0.078)**	**0.95**	(0.88-0.98)	**0.96**	(0.92-0.98)	**0.92**	(0.83-0.96)	**0.97**	(0.93-0.98)	**0.96**	(0.93-0.98)
Eccentric Peak Power/ Concentric Peak Power Ratio	**0.501 (0.126)**	**0.82**	(0.63-0.91)	**0.81**	(0.62-0.91)	**0.87**	(0.69-0.94)	**0.80**	(0.60-0.90)	**0.89**	(0.80-0.94)
P2 Concentric Impulse/ P1 Concentric Impulse Ratio	**0.599 (0.116)**	**0.91**	(0.81-0.95)	**0.89**	(0.78-0.94)	**0.85**	(0.68-0.93)	**0.94**	(0.88-0.97)	**0.92**	(0.85-0.96)
Time to Braking Phase (s)	**0.179 (0.053)**	**0.88**	(0.77-0.94)	**0.88**	(0.76-0.94)	**0.86**	(0.72-0.93)	**0.74**	(0.48-0.87)	**0.91**	(0.85-0.95)
Eccentric Duration (ms)	**513 (85)**	**0.93**	(0.87-0.97)	**0.91**	(0.82-0.96)	**0.94**	(0.88-0.97)	**0.81**	(0.61-0.91)	**0.95**	(0.91-0.97)
Braking Phase Duration (s)	**0.334 (0.054)**	**0.90**	(0.81-0.95)	**0.88**	(0.76-0.94)	**0.93**	(0.85-0.96)	**0.81**	(0.62-0.91)	**0.93**	(0.88-0.96)
Eccentric Acceleration Phase Duration (s)	**0.327 (0.066)**	**0.92**	(0.84-0.96)	**0.87**	(0.74-0.93)	**0.92**	(0.83-0.96)	**0.75**	(0.50-0.88)	**0.93**	(0.88-0.96)
Eccentric Deceleration Phase Duration (s)	**0.186 (0.033)**	**0.87**	(0.63-0.94)	**0.95**	(0.90-0.97)	**0.89**	(0.74-0.95)	**0.82**	(0.64-0.91)	**0.93**	(0.86-0.97)
Concentric Duration (ms)	**280 (33)**	**0.94**	(0.89-0.97)	**0.96**	(0.93-0.98)	**0.97**	(0.94-0.99)	**0.95**	(0.90-0.98)	**0.97**	(0.95-0.99)
Contraction Time (ms)	**793 (111)**	**0.95**	(0.90-0.97)	**0.94**	(0.88-0.97)	**0.95**	(0.91-0.98)	**0.86**	(0.71-0.93)	**0.96**	(0.94-0.98)
Concentric Time to Peak Force (ms)	**28.9 (46.2)**	**0.02**	(-0.98-0.51)	**0.19**	(-0.67-0.60)	**0.75**	(0.50-0.88)	**0.93**	(0.86-0.97)	**0.48**	(0.08-0.73)
Movement Start to Peak Force (s)	**0.524 (0.098)**	**0.73**	(0.47-0.86)	**0.83**	(0.65-0.91)	**0.76**	(0.52-0.88)	**0.86**	(0.71-0.93)	**0.84**	(0.71-0.91)

Variables	Mean (±SD)	Condition 1 M-Tu	Condition 2 M-Th	Condition 3 Tu-Th	Condition 4 M-M	Condition 5 M-Tu-Th
Movement Start to Peak Power (s)	**0.733 (0.111)**	**0.95** (0.90-0.97)	**0.94** (0.88-0.97)	**0.96** (0.91-0.98)	**0.86** (0.71-0.93)	**0.97** (0.94-0.98)
Flight Time (ms)	**607 (42)**	**0.97** (0.91-0.99)	**0.98** (0.95-0.99)	**0.98** (0.92-0.99)	**0.95** (0.88-0.98)	**0.98** (0.97-0.99)
Minimum Eccentric Force (N)	**141 (148)**	**0.96** (0.92-0.98)	**0.93** (0.86-0.97)	**0.93** (0.85-0.96)	**0.80** (0.60-0.90)	**0.96** (0.93-0.98)
Eccentric Mean Force (N)	**1011 (118)**	**0.997** (0.99-1.00)	**0.997** (0.99-1.00)	**0.994** (0.95-1.00)	**0.995** (0.99-1.00)	**0.997** (0.99-1.00)
Eccentric Mean Braking Force (N)	**1276 (163)**	**0.95** (0.90-0.98)	**0.92** (0.83-0.96)	**0.91** (0.82-0.96)	**0.92** (0.84-0.96)	**0.95** (0.91-0.97)
Eccentric Mean Deceleration Force (N)	**1954 (336)**	**0.93** (0.73-0.97)	**0.96** (0.92-0.98)	**0.93** (0.75-0.97)	**0.90** (0.81-0.95)	**0.96** (0.91-0.98)
Eccentric Peak Force (N)	**2582 (405)**	**0.91** (0.38-0.97)	**0.94** (0.89-0.97)	**0.90** (0.66-0.96)	**0.89** (0.79-0.95)	**0.94** (0.86-0.98)
Eccentric Peak Force/ BM ($N.kg^{-1}$)	**25.1 (2.5)**	**0.80** (0.07-0.93)	**0.87** (0.74-0.93)	**0.80** (0.45-0.91)	**0.77** (0.54-0.89)	**0.87** (0.71-0.94)
Force at Zero Velocity (N)	**2548 (402)**	**0.93** (0.54-0.98)	**0.96** (0.91-0.98)	**0.91** (0.72-0.96)	**0.92** (0.84-0.96)	**0.95** (0.89-0.98)
Concentric Mean Force (N)	**1994 (277)**	**0.98** (0.95-0.99)	**0.99** (0.98-1.00)	**0.98** (0.95-0.99)	**0.97** (0.92-0.98)	**0.99** (0.98-0.99)
Concentric Mean Force/ BM ($N.kg^{-1}$)	**19.39 (1.3)**	**0.93** (0.85-0.96)	**0.96** (0.91-0.98)	**0.95** (0.90-0.98)	**0.86** (0.69-0.93)	**0.96** (0.93-0.98)
Concentric Peak Force (N)	**2567 (396)**	**0.94** (0.35-0.98)	**0.97** (0.93-0.98)	**0.92** (0.73-0.97)	**0.92** (0.83-0.96)	**0.96** (0.90-0.98)
Concentric Peak Force/ BM ($N.kg^{-1}$)	**25 (2.3)**	**0.86** (0.10-0.96)	**0.91** (0.81-0.95)	**0.83** (0.56-0.93)	**0.80** (0.59-0.90)	**0.91** (0.78-0.96)
Force at Peak Power (N)	**2058 (288)**	**0.97** (0.94-0.99)	**0.96** (0.92-0.98)	**0.97** (0.93-0.99)	**0.93** (0.86-0.97)	**0.98** (0.96-0.99)
Peak Net Takeoff Force/ BM ($N.kg^{-1}$)	**15.42 (2.34)**	**0.82** (-0.07-0.95)	**0.87** (0.73-0.93)	**0.81** (0.48-0.92)	**0.74** (0.48-0.87)	**0.88** (0.71-0.95)
Peak Landing Force (N)	**8539 (2349)**	**0.73** (0.45-0.86)	**0.80** (0.60-0.90)	**0.83** (0.66-0.91)	**0.77** (0.44-0.89)	**0.86** (0.74-0.92)
Peak Landing Force/ BM (N)	**83.7 (23.3)**	**0.71** (0.41-0.85)	**0.80** (0.60-0.90)	**0.82** (0.64-0.91)	**0.75** (0.43-0.88)	**0.85** (0.73-0.92)
Landing Net Peak Force/ BM ($N.kg^{-1}$)	**73.9 (23.3)**	**0.71** (0.41-0.85)	**0.80** (0.59-0.90)	**0.82** (0.64-0.91)	**0.75** (0.43-0.89)	**0.85** (0.73-0.92)
Jump Height (FT) Relative Peak Landing Force ($N.cm^{-1}$)	**191 (56)**	**0.81** (0.61-0.90)	**0.82** (0.63-0.91)	**0.88** (0.77-0.94)	**0.80** (0.56-0.90)	**0.89** (0.81-0.94)
Eccentric Unloading Impulse (Ns)	**169 (28)**	**0.90** (0.75-0.95)	**0.90** (0.80-0.95)	**0.91** (0.66-0.97)	**0.86** (0.71-0.93)	**0.93** (0.87-0.97)
Eccentric Braking Impulse (Ns)	**84.9 (18.4)**	**0.75** (0.51-0.88)	**0.74** (0.48-0.87)	**0.76** (0.53-0.88)	**0.68** (0.35-0.84)	**0.82** (0.68-0.90)
Eccentric Deceleration Impulse (Ns)	**169 (28)**	**0.90** (0.75-0.95)	**0.90** (0.81-0.95)	**0.92** (0.64-0.97)	**0.86** (0.72-0.93)	**0.94** (0.87-0.97)
Concentric Impulse 50ms (Ns)	**72.4 (15.2)**	**0.93** (0.70-0.97)	**0.95** (0.91-0.98)	**0.90** (0.75-0.96)	**0.92** (0.84-0.96)	**0.95** (0.90-0.98)
Concentric Impulse 100ms (Ns)	**133 (28)**	**0.95** (0.84-0.98)	**0.97** (0.93-0.98)	**0.94** (0.83-0.97)	**0.94** (0.88-0.97)	**0.97** (0.93-0.98)

Variables	Mean (±SD)	Condition 1 M-Tu	Condition 2 M-Th	Condition 3 Tu-Th	Condition 4 M-M	Condition 5 M-Tu-Th
Concentric Impulse (Ns)	**273 (33)**	**0.93** (0.85-0.96)	**0.97** (0.94-0.98)	**0.94** (0.87-0.97)	**0.92** (0.82-0.96)	**0.96** (0.93-0.98)
P1 Concentric Impulse (Ns)	**172 (24)**	**0.91** (0.80-0.96)	**0.95** (0.89-0.97)	**0.90** (0.75-0.96)	**0.93** (0.86-0.97)	**0.95** (0.90-0.97)
P2 Concentric Impulse (Ns)	**101 (18)**	**0.93** (0.86-0.97)	**0.93** (0.87-0.97)	**0.90** (0.81-0.95)	**0.93** (0.81-0.97)	**0.95** (0.91-0.97)
Landing Impulse (Ns)	**57.6 (25.5)**	**0.76** (0.52-0.88)	**0.77** (0.53-0.88)	**0.92** (0.84-0.96)	**0.61** (0.20-0.81)	**0.88** (0.78-0.93)
Eccentric Mean Power (W)	**873 (142)**	**0.88** (0.73-0.94)	**0.90** (0.80-0.95)	**0.90** (0.69-0.96)	**0.82** (0.64-0.91)	**0.93** (0.86-0.96)
Eccentric Mean Power / BM (W.kg.$^{-1}$)	**8.5 (0.99)**	**0.80** (0.57-0.90)	**0.85** (0.69-0.92)	**0.84** (0.59-0.93)	**0.76** (0.52-0.88)	**0.88** (0.78-0.94)
Eccentric Peak Power (W)	**2542 (636)**	**0.86** (0.63-0.94)	**0.87** (0.73-0.93)	**0.88** (0.57-0.95)	**0.78** (0.55-0.89)	**0.91** (0.83-0.96)
Eccentric Peak Power BM (W.kg.$^{-1}$)	**24.7 (5.1)**	**0.82** (0.53-0.92)	**0.84** (0.69-0.92)	**0.85** (0.50-0.94)	**0.75** (0.49-0.88)	**0.89** (0.78-0.94)
Concentric Mean Power (W)	**2942 (455)**	**0.91** (0.79-0.96)	**0.95** (0.91-0.98)	**0.93** (0.83-0.97)	**0.87** (0.73-0.94)	**0.95** (0.91-0.98)
Concentric Mean Power/ BM (W.kg.$^{-1}$)	**28.7 (3.3)**	**0.85** (0.67-0.93)	**0.92** (0.84-0.96)	**0.90** (0.78-0.95)	**0.79** (0.57-0.90)	**0.92** (0.86-0.96)
Peak Power (W)	**5150 (746)**	**0.92** (0.83-0.96)	**0.95** (0.90-0.98)	**0.94** (0.88-0.97)	**0.87** (0.68-0.94)	**0.96** (0.92-0.98)
Peak Power/ BM (W.kg.$^{-1}$)	**50.2 (5.6)**	**0.86** (0.73-0.93)	**0.91** (0.83-0.96)	**0.92** (0.84-0.96)	**0.80** (0.52-0.91)	**0.93** (0.88-0.96)
Mean Eccentric Concentric Power Time (W.s.$^{-1}$)	**2085 (488)**	**0.93** (0.85-0.97)	**0.96** (0.91-0.98)	**0.93** (0.84-0.97)	**0.85** (0.68-0.93)	**0.96** (0.92-0.98)
Peak Landing Power (W)	**25140 (7164)**	**0.72** (0.45-0.86)	**0.80** (0.60-0.90)	**0.83** (0.66-0.91)	**0.79** (0.49-0.90)	**0.85** (0.74-0.92)
Eccentric Peak Velocity (m.s.$^{-1}$)	**1.65 (0.2)**	**0.83** (0.63-0.92)	**0.85** (0.70-0.93)	**0.88** (0.61-0.95)	**0.80** (0.59-0.90)	**0.90** (0.81-0.95)
Concentric Peak Velocity (m.s.$^{-1}$)	**2.77 (0.2)**	**0.83** (0.67-0.92)	**0.92** (0.85-0.96)	**0.89** (0.78-0.95)	**0.82** (0.62-0.92)	**0.92** (0.86-0.96)
Velocity at Peak Power (m.s.$^{-1}$)	**2.47 (0.34)**	**0.85** (0.69-0.92)	**0.31** (-0.37-0.65)	**0.35** (-0.30-0.68)	**0.32** (-0.34-0.66)	**0.47** (0.07-0.72)
Vertical Velocity at Takeoff (m.s.$^{-1}$)	**2.66 (0.21)**	**0.84** (0.69-0.92)	**0.93** (0.85-0.96)	**0.89** (0.79-0.95)	**0.83** (0.63-0.92)	**0.92** (0.86-0.96)
Peak Landing Velocity (m.s^{-1})	**1.01 (0.23)**	**0.78** (0.57-0.89)	**0.80** (0.59-0.9)	**0.81** (0.62-0.91)	**0.44** (-0.15-0.73)	**0.87** (0.78-0.93)
Eccentric Braking RFD 100ms (N.s^{-1})	**4628 (2830)**	**0.79** (0.54-0.90)	**0.80** (0.59-0.9)	**0.82** (0.64-0.91)	**0.76** (0.49-0.89)	**0.86** (0.75-0.93)
Eccentric Braking RFD 100ms/ BM (N.s.kg^{-1})	**45.6 (28)**	**0.80** (0.57-0.91)	**0.82** (0.64-0.91)	**0.83** (0.65-0.91)	**0.77** (0.52-0.89)	**0.87** (0.77-0.93)
Eccentric Braking RFD (N.s^{-1})	**7565 (2379)**	**0.93** (0.84-0.97)	**0.92** (0.85-0.96)	**0.91** (0.79-0.96)	**0.90** (0.80-0.95)	**0.95** (0.90-0.97)
Eccentric Braking RFD/ BM (N.s.kg^{-1})	**73.7 (20.9)**	**0.92** (0.82-0.96)	**0.92** (0.84-0.96)	**0.90** (0.79-0.95)	**0.88** (0.76-0.94)	**0.94** (0.89-0.97)
Eccentric Deceleration RFD (N.s^{-1})	**8848 (3380)**	**0.91** (0.62-0.96)	**0.95** (0.89-0.97)	**0.90** (0.76-0.95)	**0.88** (0.75-0.94)	**0.94** (0.88-0.97)
Eccentric Deceleration RFD/ BM (N.s.kg^{-1})	**85.8 (28.6)**	**0.88** (0.53-0.95)	**0.93** (0.87-0.97)	**0.88** (0.72-0.94)	**0.85** (0.69-0.92)	**0.93** (0.85-0.96)

Variables	Mean (±SD)	Condition 1 M-Tu	Condition 2 M-Th	Condition 3 Tu-Th	Condition 4 M-M	Condition 5 M-Tu-Th
Concentric RPD 50ms (W.s^{-1})	**33044 (9725)**	**0.92** (0.75-0.97)	**0.95** (0.9-0.97)	**0.91** (0.78-0.96)	**0.91** (0.81-0.95)	**0.95** (0.90-0.98)
Concentric RPD 50ms/BM (W.s.kg^{-1})	**321 (80)**	**0.89** (0.67-0.96)	**0.93** (0.86-0.97)	**0.89** (0.73-0.95)	**0.88** (0.75-0.94)	**0.93** (0.87-0.97)
Concentric RPD 100ms (W.s^{-1})	**27580 (8407)**	**0.95** (0.88-0.97)	**0.96** (0.93-0.98)	**0.96** (0.88-0.98)	**0.93** (0.86-0.97)	**0.97** (0.94-0.98)
Concentric RPD 100ms/BM (W.s.kg^{-1})	**267 (67)**	**0.93** (0.84-0.96)	**0.95** (0.90-0.98)	**0.94** (0.85-0.98)	**0.90** (0.81-0.95)	**0.96** (0.93-0.98)
Concentric RPD (W.s^{-1})	**24190 (6726)**	**0.95** (0.90-0.98)	**0.97** (0.94-0.98)	**0.98** (0.94-0.99)	**0.92** (0.83-0.96)	**0.98** (0.96-0.99)
Concentric RPD/BM (W.s.kg^{-1})	**235 (51)**	**0.93** (0.86-0.96)	**0.95** (0.89-0.97)	**0.97** (0.93-0.99)	**0.87** (0.74-0.94)	**0.97** (0.94-0.98)
Concentric RFD 50ms (N.s^{-1})	**-4251 (2142)**	**0.63** (-0.09-0.85)	**0.74** (0.49-0.87)	**0.72** (0.37-0.87)	**0.75** (0.48-0.87)	**0.77** (0.54-0.89)
Concentric RFD 100ms (N.s^{-1})	**-4277 (1964)**	**0.77** (0.11-0.91)	**0.81** (0.62-0.91)	**0.78** (0.53-0.89)	**0.84** (0.68-0.92)	**0.84** (0.68-0.92)
Concentric RFD 200ms (N.s^{-1})	**-3298 (3611)**	**0.96** (0.91-0.98)	**0.97** (0.93-0.98)	**0.96** (0.92-0.98)	**0.95** (0.89-0.97)	**0.97** (0.95-0.99)
Concentric RFD (N.s^{-1})	**322 (525)**	**0.38** (-0.20-0.69)	**0.60** (0.21-0.8)	**0.79** (0.59-0.90)	**0.41** (-0.22-0.71)	**0.72** (0.50-0.85)
Concentric RFD/BM (N.s.kg^{-1})	**3 (5)**	**0.37** (-0.23-0.68)	**0.63** (0.26-0.82)	**0.78** (0.55-0.89)	**0.44** (-0.16-0.73)	**0.71** (0.49-0.85)
Landing RFD 50ms (N.s^{-1})	**38353 (25471)**	**0.78** (0.57-0.89)	**0.80** (0.60-0.90)	**0.89** (0.78-0.95)	**0.75** (0.50-0.88)	**0.87** (0.77-0.93)
Landing RFD (N.s^{-1})	**604117 (273813)**	**0.73** (0.46-0.86)	**0.76** (0.51-0.88)	**0.76** (0.53-0.88)	**0.81** (0.61-0.91)	**0.82** (0.67-0.90)
Jump Height (FT) Relative Landing RFD (N.s.cm^{-1})	**13265 (5796)**	**0.74** (0.48-0.87)	**0.74** (0.48-0.87)	**0.76** (0.51-0.88)	**0.80** (0.60-0.90)	**0.82** (0.67-0.90)

Appendix 6: Measurement characteristics for variables calculated by Mean$_3$

Variable	Signal CV (95% CI)	Noise CV (95% CI)	SNR	Mean	SD
Eccentric					
Braking Phase Duration [s]	6.8 (6.2-9.5)	5.3 (4.9-6.4)	**1.3**	0.3	0.05
Countermovement Depth [cm] *	**10.1 (9.2-14.1)**	**5.4 (5-6.6)**	**1.9**	**44.6**	**6.7**
Eccentric Acceleration Phase Duration [s]	8.8 (8.0-12.3)	6.7 (6.2-8.1)	**1.3**	0.3	0.06
Eccentric Braking Impulse [Ns]	11.6 (10.5-16.1)	10.5 (9.7-12.7)	**1.1**	88	21
Eccentric Braking RFD 100ms-BM [N.s.kg $^{-1}$]	38.9 (35.2-54.3)	31.9 (29.4-38.4)	**1.2**	49	32
Eccentric Braking RFD-BM [N.s.kg $^{-1}$]	10.9 (9.9-15.2)	9.4 (8.7-11.3)	**1.2**	75	22
Eccentric Deceleration Impulse [Ns]	5.8 (5.2-8.1)	5.1 (4.7-6.2)	**1.1**	171	30
Eccentric Deceleration Phase Duration [s]	7.1 (6.4-9.9)	5.6 (5.1-6.7)	**1.3**	0.2	0.04
Eccentric Deceleration RFD-BM [N.s.kg $^{-1}$]	13.8 (12.5-19.3)	11.8 (10.9-14.3)	**1.2**	85	30
Eccentric Duration [ms] *	**7.5 (6.8-10.4)**	**5.0 (4.6-6.1)**	**1.5**	**512**	**65**
Eccentric Mean Braking Force [N]	3.7 (3.3-5.1)	3.1 (2.9-3.8)	**1.2**	1,279	158
Eccentric Mean Deceleration Force [N]	4.0 (3.6-5.6)	4.0 (3.7-4.8)	**1.0**	1,953	294
Eccentric Mean Power-BM [W.kg $^{-1}$]	6.3 (5.7-8.8)	5.7 (5.2-6.8)	**1.1**	8.6	1.1
Eccentric Peak Force-BM [N.kg $^{-1}$]	4.3 (3.9-6.0)	4.0 (3.7-4.9)	**1.1**	25	2.8
Eccentric Peak Power-BM [W.kg $^{-1}$]	11.2 (10.1-15.7)	8.7 (8.0-10.4)	1.3	26	5.7
Eccentric Peak Velocity [m.s $^{-1}$]	6.2 (5.6-8.6)	4.9 (4.5-5.9)	**1.3**	1.7	0.2
Eccentric Unloading Impulse [Ns]	5.8 (5.2-8.0)	5.2 (4.8-6.3)	**1.1**	171	30
Force at Zero Velocity [N]	5.0 (4.5-7.0)	4.1 (3.8-5.0)	**1.2**	2,501	353.1
Minimum Eccentric Force [N]	44.5 (40.3-62.4)	37.9 (34.9-45.7)	**1.2**	130	111
Time to Braking Phase [s]	12.4 (11.2-17.3)	12.9 (11.9-15.5)	**1.0**	0.2	0.05
Concentric					
Concentric Duration [ms]	3.4 (3.1-4.8)	3.2 (3-3.9)	**1.1**	287	33
Concentric Impulse [Ns] *	**5.5 (5.0-7.7)**	**3.5 (3.2-4.2)**	**1.6**	**268**	**30**
Concentric Impulse 100ms [Ns] *	**8.3 (7.5-11.6)**	**5.0 (4.6-6.1)**	**1.7**	**126**	**21**
Concentric Impulse 100ms-Concentric Impulse Ratio	5.3 (4.8-7.4)	4.7 (4.3-5.6)	**1.1**	0.5	0.1
Concentric Impulse 50ms [Ns] *	**8.7 (7.9-12.1)**	**5.8 (5.4-7.0)**	**1.5**	**70**	**13**

Variable	Signal CV (95% CI)	Noise CV (95% CI)	SNR	Mean	SD
Concentric Mean Force-BM [N.kg $^{-1}$] *	**2.3 (2.1-3.3)**	**1.7 (1.6-2.1)**	**1.4**	**19**	**1.4**
Concentric Mean Power-BM [W.kg $^{-1}$] *	**7.1 (6.4-9.9)**	**4.5 (4.1-5.4)**	**1.6**	**28**	**3.9**
Concentric Peak Force-BM [N.kg $^{-1}$]	4.1 (3.7-5.8)	3.2 (2.9-3.8)	**1.3**	25	2.5
Concentric Peak Power-BM [W.kg $^{-1}$]	5.5 (5.0-7.7)	4.3 (3.9-5.1)	**1.3**	50	6.2
Concentric Peak Velocity [m.s $^{-1}$] **	**4.6 (4.2-6.4)**	**3.1 (2.9-3.8)**	**1.5**	**2.8**	**0.2**
Concentric RPD 100ms-BM [W.s.kg $^{-1}$] *	**11.5 (10.4-16.0)**	**6.8 (6.3-8.2)**	**1.7**	**250**	**62**
Concentric RPD 50ms-BM [W.s.kg $^{-1}$] *	**13.1 (11.9-18.3)**	**8.1 (7.5-9.8)**	**1.6**	**307**	**81**
Concentric RPD-BM [W.s.kg $^{-1}$]	6.2 (5.6-8.6)	5.3 (4.9-6.4)	**1.2**	225	46
Force at Peak Power [N]	1.6 (1.4-2.2)	2.1 (2.0-2.6)	**0.8**	2,019	191
P1 Concentric Impulse [Ns] **	**7.6 (6.9-10.6)**	**3.9 (3.6-4.7)**	**1.9**	**167**	**21**
P2 Concentric Impulse [Ns]	6.0 (5.4-8.4)	5.3 (4.9-6.4)	**1.1**	101	16
P2 Concentric Impulse-P1 Concentric Impulse Ratio *	**8.7 (7.8-12.1)**	**5.9 (5.4-7.1)**	**1.5**	**0.6**	**0.1**
Velocity at Peak Power [m.s $^{-1}$] *	**4.9 (4.5-6.9)**	**3.2 (3.0-3.9)**	**1.5**	**2.5**	**0.2**
Vertical Velocity at Takeoff [m.s $^{-1}$] *	**5.0 (4.5-6.9)**	**3.4 (3.1-4.1)**	**1.5**	**2.6**	**0.2**
Landing					
Jump Height FT Relative Landing RFD [N.s.cm $^{-1}$]	23.8 (21.6-33.3)	27.7 (25.5-33.4)	**0.9**	12,130	5,882
Jump Height FT Relative Peak Landing Force [N.cm $^{-1}$]	11.1 (10.1-15.6)	11.9 (11-14.3)	**0.9**	187	51
Landing Impulse [Ns]	14.1 (12.8-19.7)	18.3 (16.9-22)	**0.8**	60	25
Landing Net Peak Force-BM [N.kg $^{-1}$]	12.4 (11.2-17.3)	13.0 (12-15.6)	**1.0**	72	22
Landing RFD [N.s $^{-1}$]	23.6 (21.3-32.9)	28.0 (25.8-33.8)	**0.8**	549,583	286,777
Landing RFD 50ms [N.s $^{-1}$] *	**23.4 (21.2-32.7)**	**17.2 (15.9-20.8)**	**1.4**	**40,209**	**23,284**
Mean Landing Power [W]	6.8 (6.1-9.4)	5.8 (5.3-7.0)	**1.2**	1,297	257
Peak Landing Acceleration [m.s.s $^{-1}$]	12.4 (11.2-17.3)	13.0 (12-15.6)	**1.0**	72	22
Peak Landing Force-BM [N.kg $^{-1}$]	10.7 (9.7-14.9)	11.3 (10.5-13.7)	**0.9**	82	22
Peak Landing Power [W]	10.1 (9.2-14.1)	12.5 (11.6-15.1)	**0.8**	23,933	7,159
Peak Landing Velocity [m.s $^{-1}$]	19.4 (17.5-27.1)	16.9 (15.5-20.3)	**1.1**	1.1	0.3
Composite					
Contraction Time [ms]	4.7 (4.3-6.6)	3.9 (3.6-4.7)	**1.2**	798	88
Peak Net Takeoff Force-BM [N.kg $^{-1}$]	7.0 (6.3-9.7)	5.7 (5.3-6.9)	**1.2**	15.4	2.6

Variable	**Signal CV (95% CI)**	**Noise CV (95% CI)**	**SNR**	**Mean**	**SD**
Peak Takeoff Acceleration [m.s.s $^{-1}$]	7.1 (6.4-9.9)	5.4 (5-6.5)	**1.3**	15.1	2.5
Positive Impulse [Ns]	6.6 (6-9.3)	10.4 (9.6-12.5)	**0.6**	820	149
Positive Takeoff Impulse [Ns] *	**3.7 (3.3-5.2)**	**2.5 (2.3-3.0)**	**1.5**	**451**	**53**
Takeoff Peak Force-BM [N.kg $^{-1}$]	4.1 (3.7-5.7)	3.3 (3.1-4.0)	**1.2**	25	2.6
Braking Phase Duration-Concentric Duration [%]*	**8.2 (7.4-11.4)**	**5.3 (4.9-6.4)**	**1.5**	**115**	**15**
Braking Phase Duration-Contraction Time [%]	4.2 (3.8-5.8)	4.4 (4.1-5.3)	**1.0**	41.2	4.8
CMJ Stiffness [N.m $^{-1}$] *	**12.0 (10.8-16.7)**	**6.6 (6.1-8.0)**	**1.8**	**5,880**	**1,172**
Contraction Time-Eccentric Duration [%] *	**3.1 (2.8-4.4)**	**1.6 (1.5-1.9)**	**1.9**	**157**	**5.8**
Eccentric Peak Power-Concentric Peak Power Ratio	11.9 (10.7-16.5)	10.8 (9.9-13)	**1.1**	0.5	0.1
Eccentric-Concentric Duration [%] *	**8.9 (8.1-12.4)**	**4.7 (4.4-5.7)**	**1.9**	**179**	**20**
Eccentric-Concentric Mean Force Ratio [%] *	**2.3 (2.1-3.2)**	**1.7 (1.6-2.1)**	**1.4**	**52**	**3.6**
Flight Time [ms] *	**1.9 (1.7-2.7)**	**1.4 (1.3-1.7)**	**1.4**	**602**	**40**
Flight Time-Contraction Time Ratio	5.0 (4.5-7.0)	4.3 (4.0-5.2)	**1.2**	0.8	0.1
Flight Time-Eccentric Duration Ratio *	**7.6 (6.9-10.6)**	**5.3 (4.9-6.4)**	**1.4**	**1.2**	**0.2**
Jump Height Flight Time [cm] *	**3.8 (3.5-5.3)**	**2.8 (2.6-3.4)**	**1.4**	**45**	**5.9**
Jump Height Imp Mom [cm] *	**10.2 (9.2-14.2)**	**6.9 (6.3-8.3)**	**1.5**	**36**	**6.4**
Lower Limb Stiffness [N.m $^{-1}$] *	**12.9 (11.7-18)**	**7.5 (6.9-9)**	**1.7**	**5,524**	**1,211**
Mean Eccentric Concentric Power-Time [W.s $^{-1}$] *	**10.6 (9.6-14.8)**	**7.4 (6.8-8.9)**	**1.4**	**2,014**	**342**
Movement Start to Peak Force [s]	8.7 (7.9-12.2)	9.9 (9.1-11.9)	**0.9**	0.5	0.10
Movement Start to Peak Power [s]	5.1 (4.6-7.2)	4.2 (3.9-5.1)	**1.2**	0.7	0.11
RSI modified [m.s $^{-1}$]	5.6 (5.1-7.9)	5.2 (4.8-6.3)	**1.1**	0.6	0.1
Total Work [J] *	**5.3 (4.8-7.5)**	**3.4 (3.1-4.1)**	**1.6**	**1,262**	**186**

* = non-overlap of 95% confidence intervals; RFD – rate of force development; RPD – rate of power development

Appendix 7: Measurement characteristics for variables calculated by Best$_{JH}$

Variable	Signal CV (95% CI)	Noise CV (95% CI)	SNR	Mean	SD
	Eccentric				
Braking Phase Duration [s]	7.2 (6.5-10.0)	6.8 (6.3-8.2)	**1.1**	0.3	0.05
Countermovement Depth [cm] *	**13.8 (12.5-19.3)**	**7.6 (7-9.2)**	**1.8**	**44.0**	**7.0**
Eccentric Acceleration Phase Duration [s] *	**12.6 (11.4-17.6)**	**7.9 (7.3-9.6)**	**1.6**	**0.3**	**0.06**
Eccentric Braking Impulse [Ns]	17.7 (16.0-24.7)	17.0 (15.7-20.5)	**1.0**	88	23
Eccentric Braking RFD 100ms-BM [N.s.kg $^{-1}$]	35.3 (32.0-49.3)	62.4 (57.5-75.2)	**0.6**	49	39
Eccentric Braking RFD-BM [N.s.kg $^{-1}$]	10.8 (9.7-15.0)	11.7 (10.8-14.1)	**0.9**	76	24
Eccentric Deceleration Impulse [Ns]	8.6 (7.8-12.0)	7.5 (6.9-9.0)	**1.1**	172	32
Eccentric Deceleration Phase Duration [s]	7.9 (7.1-11.0)	8.2 (7.5-9.8)	**1.0**	0.2	0.03
Eccentric Deceleration RFD-BM [N.s.kg $^{-1}$]	13.8 (12.5-19.3)	16.7 (15.4-20.1)	**0.8**	87	31
Eccentric Duration [ms] *	**9.8 (8.9-13.7)**	**6.0 (5.5-7.2)**	**1.6**	**501**	**62**
Eccentric Mean Braking Force [N]	4.4 (4.0-6.2)	3.9 (3.6-4.7)	**1.1**	1,283	168
Eccentric Mean Deceleration Force [N]	5.1 (4.6-7.1)	5.9 (5.4-7.1)	**0.9**	1,963	313
Eccentric Mean Power-BM [W.kg $^{-1}$]	7.5 (6.7-10.4)	7.9 (7.3-9.5)	**0.9**	8.8	1.1
Eccentric Peak Force-BM [N.kg $^{-1}$]	4.4 (4.0-6.1)	5.2 (4.8-6.3)	**0.8**	25	3.0
Eccentric Peak Power-BM [W.kg $^{-1}$]	13.9 (12.6-19.4)	13.1 (12.1-15.8)	**1.1**	26	6.4
Eccentric Peak Velocity [m.s $^{-1}$]	8.9 (8.1-12.5)	7.4 (6.8-8.9)	**1.2**	1.7	0.2
Eccentric Unloading Impulse [Ns]	8.6 (7.8-12)	7.6 (7.0-9.2)	**1.1**	172	32
Force at Zero Velocity [N]	4.7 (4.3-6.6)	5.1 (4.7-6.2)	**0.9**	2,515	363
Minimum Eccentric Force [N]	101.1 (91.4-141.8)	107.3 (98.7-130.4)	**0.9**	132	121
Time to Braking Phase [s] *	**23.8 (21.6-33.2)**	**16.3 (15-19.6)**	**1.5**	**0.2**	**0.05**
	Concentric				
Concentric Duration [ms]	3.7 (3.3-5.1)	3.9 (3.6-4.7)	**0.9**	287	33
Concentric Impulse [Ns]	5.8 (5.3-8.2)	4.8 (4.4-5.7)	**1.2**	270	31
Concentric Impulse 100ms [Ns]	7.8 (7.0-10.8)	6.6 (6.1-7.9)	**1.2**	127	21
Concentric Impulse 100ms-Concentric Impulse Ratio	5.4 (4.9-7.6)	5.1 (4.7-6.1)	**1.1**	0.5	0.1
Concentric Impulse 50ms [Ns]	7.9 (7.1-11.0)	7.6 (7.0-9.2)	**1.0**	70	13

Variable	Signal CV (95% CI)	Noise CV (95% CI)	SNR	Mean	SD
Concentric Mean Force-BM [N.kg -1] *	**3.2 (2.9-4.4)**	**2.4 (2.2-2.9)**	**1.3**	**19**	**1.4**
Concentric Mean Power-BM [W.kg -1]	8.0 (7.3-11.2)	6.4 (5.9-7.7)	**1.2**	28	3.9
Concentric Peak Force-BM [N.kg -1]	3.7 (3.3-5.1)	3.6 (3.3-4.3)	**1.0**	25	2.6
Concentric Peak Power-BM [W.kg -1]	7.6 (6.9-10.6)	6.0 (5.5-7.2)	**1.3**	50	6.4
Concentric Peak Velocity [m.s $^{-1}$]	5.1 (4.6-7.0)	4.4 (4-5.2)	**1.2**	2.8	0.2
Concentric RPD 100ms-BM [W.s.kg $^{-1}$]	11.6 (10.5-16.1)	9.2 (8.5-11.1)	**1.3**	253	62
Concentric RPD 50ms-BM [W.s.kg $^{-1}$]	12.4 (11.2-17.3)	11.1 (10.2-13.3)	**1.1**	311	82
Concentric RPD-BM [W.s.kg $^{-1}$]	9.3 (8.5-13.0)	7.5 (6.9-9.0)	**1.2**	226	45
Force at Peak Power [N]	3.0 (2.7-4.2)	3.4 (3.1-4.0)	**0.9**	2,012	192
P1 Concentric Impulse [Ns]	6.7 (6.1-9.4)	5.8 (5.3-7.0)	**1.2**	168	22
P2 Concentric Impulse [Ns]	7.5 (6.8-10.4)	6.8 (6.3-8.2)	**1.1**	102	17
P2 Concentric Impulse-P1 Concentric Impulse Ratio	7.7 (7.0-10.8)	8.0 (7.4-9.6)	**1.0**	0.6	0.1
Velocity at Peak Power [m.s $^{-1}$]	5.0 (4.5-7.0)	4.4 (4.0-5.3)	**1.1**	2.5	0.2
Vertical Velocity at Takeoff [m.s $^{-1}$]	5.5 (4.9-7.6)	4.7 (4.3-5.6)	**1.2**	2.7	0.2
Landing					
Jump Height FT Relative Landing RFD [N.s.cm $^{-1}$]	42.0 (38-58.6)	45.4 (41.8-54.7)	**0.9**	13,035	6,941
Jump Height FT Relative Peak Landing Force [N.cm $^{-1}$]*	**30.8 (27.9-43.0)**	**19.9 (18.4-24.0)**	**1.5**	**189**	**59**
Landing Impulse [Ns]	28.3 (25.6-39.5)	30.7 (28.3-36.9)	**0.9**	57	25
Landing Net Peak Force-BM [N.kg $^{-1}$] *	**36.9 (33.4-51.5)**	**23.2 (21.3-27.9)**	**1.6**	**75**	**26**
Landing RFD [N.s $^{-1}$]	40.5 (36.6-56.4)	46.5 (42.9-56.0)	**0.9**	601,063	334,686
Landing RFD 50ms [N.s $^{-1}$]	17.3 (15.7-24.2)	32.2 (29.7-38.8)	**0.5**	38,033.3	22,716
Mean Landing Power [W] *	**10.2 (9.2-14.2)**	**6.3 (5.8-7.6)**	**1.6**	**1,322**	**264**
Peak Landing Acceleration [m.s $^{-1}$] *	**36.9 (33.4-51.5)**	**23.2 (21.3-27.9)**	**1.6**	**75**	**26**
Peak Landing Force-BM [N.kg $^{-1}$] *	**28.6 (25.9-39.9)**	**20.1 (18.5-24.2)**	**1.4**	**85**	**26**
Peak Landing Power [W] *	**30.6 (27.7-42.7)**	**22.1 (20.4-26.7)**	**1.4**	**25,049**	**8,310**
Peak Landing Velocity [m.s $^{-1}$]	20.3 (18.4-28.4)	21.9 (20.2-26.4)	**0.9**	1.1	0.3
Composite					
Contraction Time [ms] *	**6.6 (5.9-9.2)**	**4.3 (4-5.2)**	**1.5**	**787**	**86**
Peak Net Takeoff Force-BM [N.kg $^{-1}$]	7.3 (6.6-10.2)	7.2 (6.6-8.7)	**1.0**	15.5	2.8

Variable	Signal CV (95% CI)	Noise CV (95% CI)	SNR	Mean	SD
Peak Takeoff Acceleration [m.s -1]	6.4 (5.8-8.9)	6.1 (5.6-7.3)	**1.0**	15.2	2.6
Positive Impulse [Ns]	13.0 (11.8-18.2)	11.1 (10.2-13.4)	**1.2**	8321	169
Positive Takeoff Impulse [Ns]	3.1 (2.8-4.3)	3.3 (3.1-4.0)	**0.9**	454	53
Takeoff Peak Force-BM [N.kg -1]	4.2 (3.8-5.9)	4.1 (3.8-5.0)	**1.0**	25	2.8
Braking Phase Duration-Concentric Duration [%]	7.9 (7.1-11.0)	7.7 (7.1-9.3)	**1.0**	115	16.4
Braking Phase Duration-Contraction Time [%]	5.8 (5.2-8.1)	6.0 (5.5-7.2)	**1.0**	41.6	5.2
CMJ Stiffness [N.m -1] *	**15.0 (13.5-20.9)**	**8.7 (8.0-10.5)**	**1.7**	**5,872**	**1,218**
Contraction Time-Eccentric Duration [%] *	**3.5 (3.2-4.9)**	**2.3 (2.1-2.8)**	**1.5**	**158**	**6.1**
Eccentric Peak Power-Concentric Peak Power Ratio	19.7 (17.9-27.5)	15.8 (14.5-19.0)	**1.2**	0.5	0.1
Eccentric-Concentric Duration [%] *	**9.8 (8.9-13.7)**	**6.6 (6.1-8.0)**	**1.5**	**175**	**19**
Eccentric-Concentric Mean Force Ratio [%]	3.1 (2.8-4.3)	2.4 (2.2-2.9)	**1.3**	52	3.6
Flight Time [ms]	1.6 (1.5-2.3)	1.4 (1.3-1.6)	**1.1**	610	40
Flight Time-Contraction Time Ratio *	**6.6 (5.9-9.1)**	**4.8 (4.5-5.8)**	**1.4**	**0.8**	**0.1**
Flight Time-Eccentric Duration Ratio *	**9.9 (8.9-13.8)**	**6.6 (6.1-7.9)**	**1.5**	**1.2**	**0.2**
Jump Height Flight Time [cm]	3.3 (3.0-4.6)	2.7 (2.5-3.3)	**1.2**	45.7	5.9
Jump Height Imp Mom [cm]	11.3 (10.2-15.7)	9.6 (8.8-11.5)	**1.2**	36.6	6.6
Lower Limb Stiffness [N.m -1] *	**15.2 (13.7-21.1)**	**9.8 (9.0-11.8)**	**1.6**	**5,519**	**1,265**
Mean Eccentric Concentric Power-Time [W.s -1] *	**13.0 (11.7-18.1)**	**8.9 (8.2-10.7)**	**1.5**	**2,083**	**360**
Movement Start to Peak Force [s]	10.7 (9.7-15.0)	13.7 (12.6-16.5)	**0.8**	0.5	0.10
Movement Start to Peak Power [s] *	**7.0 (6.4-9.8)**	**4.6 (4.3-5.6)**	**1.5**	**0.7**	**0.11**
RSI modified [m.s -1]	7.0 (6.3-9.8)	6.0 (5.5-7.2)	**1.2**	0.6	0.1
Total Work [J]	4.6 (4.2-6.5)	4.3 (4.0-5.2)	**1.1**	1,273.9	187

* = non-overlap of 95% confidence intervals; RFD – rate of force development; RPD – rate of power development

Appendix 8: Measurement characteristics for variables calculated by Best$_{FTCT}$

Variable	Signal CV (95% CI)	Noise CV (95% CI)	SNR	Mean	SD
Eccentric					
Braking Phase Duration [s]	7.3 (6.6-10.2)	7.0 (6.4-9.0)	**1.0**	0.3	0.05
Countermovement Depth [cm] *	**9.3 (8.4-13.0)**	**6.3 (5.8-8.1)**	**1.5**	**43.5**	**7.3**
Eccentric Acceleration Phase Duration [s] *	**8.0 (7.2-11.1)**	**4.3 (3.9-5.5)**	**1.9**	**0.3**	**0.05**
Eccentric Braking Impulse [Ns]	16.1 (14.6-22.5)	15.5 (14.2-20.0)	**1.0**	87	23
Eccentric Braking RFD 100ms-BM [N.s.kg $^{-1}$]	46.9 (42.4-65.4)	71.7 (65.4-92.1)	**0.7**	50	37
Eccentric Braking RFD-BM [N.s.kg $^{-1}$]	12.4 (11.3-17.4)	10.1 (9.2-13.0)	**1.2**	78	23
Eccentric Deceleration Impulse [Ns]	6.6 (6-9.3)	6.4 (5.9-8.3)	**1.0**	172	31
Eccentric Deceleration Phase Duration [s]	9.8 (8.9-13.7)	7.4 (6.7-9.5)	**1.3**	0.2	0.04
Eccentric Deceleration RFD-BM [N.s.kg $^{-1}$]	18.4 (16.7-25.7)	14.3 (13.1-18.4)	**1.3**	89	33
Eccentric Duration [ms] *	**7.5 (6.8-10.4)**	**3.0 (2.8-3.9)**	**2.5**	**481**	**56**
Eccentric Mean Braking Force [N]	4.0 (3.6-5.6)	4.3 (3.9-5.5)	**0.9**	1,281	166
Eccentric Mean Deceleration Force [N]	6.2 (5.6-8.6)	5.1 (4.6-6.5)	**1.2**	1,980	300
Eccentric Mean Power-BM [W.kg $^{-1}$]	6.2 (5.6-8.7)	6.0 (5.5-7.7)	**1.0**	8.8	1.1
Eccentric Peak Force-BM [N.kg $^{-1}$]	5.9 (5.4-8.3)	4.4 (4.0-5.7)	**1.3**	25	3.0
Eccentric Peak Power-BM [W.kg $^{-1}$]	12.1 (11.0-16.9)	11.8 (10.8-15.1)	**1.0**	26	6.1
Eccentric Peak Velocity [m.s $^{-1}$]	6.6 (6.0-9.2)	6.2 (5.6-7.9)	**1.1**	1.7	0.2
Eccentric Unloading Impulse [Ns]	6.5 (5.8-9.0)	6.5 (5.9-8.3)	**1.0**	172	31
Force at Zero Velocity [N]	6.4 (5.8-8.9)	4.7 (4.3-6.1)	**1.4**	2,527	353
Minimum Eccentric Force [N] *	**180.4 (163.2-254.1)**	**119.7 (109.1-155)**	**1.5**	**110**	**101**
Time to Braking Phase [s]	16.3 (14.8-22.8)	12.3 (11.3-15.8)	**1.3**	0.2	0.05
Concentric					
Concentric Duration [ms]	4.5 (4.1-6.3)	4.0 (3.6-5.1)	**1.1**	283	33
Concentric Impulse [Ns] *	**6.3 (5.7-8.8)**	**4.2 (3.8-5.4)**	**1.5**	**270**	**30**
Concentric Impulse 100ms [Ns] *	**8.4 (7.6-11.7)**	**5.7 (5.2-7.3)**	**1.5**	**128**	**21**
Concentric Impulse 100ms-Concentric Impulse Ratio	5.9 (5.3-8.2)	4.7 (4.3-6.1)	**1.3**	0.5	0.1
Concentric Impulse 50ms [Ns] *	**9.5 (8.6-13.3)**	**6.6 (6.1-8.5)**	**1.4**	**71**	**13**
Concentric Mean Force-BM [N.kg $^{-1}$]	2.0 (1.8-2.8)	1.8 (1.6-2.3)	**1.1**	19	1.4

Variable	Signal CV (95% CI)	Noise CV (95% CI)	SNR	Mean	SD
Concentric Mean Power-BM [W.kg $^{-1}$] *	**7.3 (6.6-10.1)**	**5.2 (4.7-6.6)**	**1.4**	**29**	**4.1**
Concentric Peak Force-BM [N.kg $^{-1}$] *	**5.1 (4.7-7.2)**	**3.6 (3.3-4.6)**	**1.4**	**25**	**2.6**
Concentric Peak Power-BM [W.kg $^{-1}$]	6.1 (5.6-8.6)	4.5 (4.1-5.7)	**1.4**	51	6.5
Concentric Peak Velocity [m.s $^{-1}$]	5.3 (4.8-7.4)	3.8 (3.5-4.9)	**1.4**	2.8	0.2
Concentric RPD 100ms-BM [W.s.kg $^{-1}$]	10.7 (9.7-14.9)	7.7 (7.1-9.9)	**1.4**	259	65
Concentric RPD 50ms-BM [W.s.kg $^{-1}$] *	**13.8 (12.5-19.2)**	**9.1 (8.3-11.7)**	**1.5**	**316**	**86**
Concentric RPD-BM [W.s.kg $^{-1}$]	5.3 (4.8-7.4)	5.5 (5.0-7.0)	**1.0**	231	48
Force at Peak Power [N]	2.7 (2.4-3.8)	2.6 (2.4-3.4)	**1.0**	2,029	200
P1 Concentric Impulse [Ns] *	**8.1 (7.4-11.4)**	**5.8 (5.3-7.4)**	**1.4**	**168**	**22**
P2 Concentric Impulse [Ns]	7.5 (6.8-10.5)	5.9 (5.4-7.6)	**1.3**	102	17
P2 Concentric Impulse-P1 Concentric Impulse Ratio	9.6 (8.7-13.4)	8.0 (7.3-10.3)	**1.2**	0.6	0.1
Velocity at Peak Power [m.s $^{-1}$] *	**5.9 (5.4-8.3)**	**4.1 (3.7-5.3)**	**1.4**	**2.5**	**0.3**
Vertical Velocity at Takeoff [m.s $^{-1}$] *	**5.8 (5.2-8.1)**	**4.1 (3.7-5.2)**	**1.4**	**2.7**	**0.2**
Landing					
Jump Height FT Relative Landing RFD [N.s.cm $^{-1}$]	53.9 (48.8-75.2)	42.7 (38.9-54.8)	**1.3**	12,569	6,862
Jump Height FT Relative Peak Landing Force [N.cm $^{-1}$]	27.9 (25.3-39.0)	24.4 (22.2-31.3)	**1.1**	188	59
Landing Impulse [Ns]	26.0 (23.5-36.2)	29.9 (27.3-38.5)	**0.9**	58	26
Landing Net Peak Force-BM [N.kg $^{-1}$]	34.3 (31.0-47.8)	28.5 (26.0-36.6)	**1.2**	74	26
Landing RFD [N.s $^{-1}$]	53.9 (48.8-75.2)	44.7 (40.8-57.4)	**1.2**	573,900	331,474
Landing RFD 50ms [N.s $^{-1}$]	23.9 (21.6-33.3)	41.1 (37.5-52.7)	**0.6**	38,779	24,157
Mean Landing Power [W] *	**10.4 (9.4-14.6)**	**5.9 (5.3-7.5)**	**1.8**	**1,302**	**261**
Peak Landing Acceleration [m.s $^{-1}$]	34.3 (31.0-47.8)	28.5 (26-36.6)	**1.2**	74	26
Peak Landing Force-BM [N.kg $^{-1}$]	25.8 (23.4-36.1)	24.5 (22.4-31.5)	**1.1**	83	26
Peak Landing Power [W]	30.3 (27.4-42.2)	24.9 (22.7-32)	**1.2**	24,437	8,341
Peak Landing Velocity [m.s $^{-1}$]	30.1 (27.3-42.0)	18.8 (17.2-24.2)	**1.6**	1.1	0.3
Composite					
Contraction Time [ms] *	**4.6 (4.1-6.4)**	**2.6 (2.3-3.3)**	**1.8**	**763**	**79**
Peak Net Takeoff Force-BM [N.kg $^{-1}$] *	**10.1 (9.1-14.1)**	**6.9 (6.3-8.9)**	**1.5**	**16**	**2.8**
Peak Takeoff Acceleration [m.s $^{-1}$] *	**9.0 (8.1-12.5)**	**6.0 (5.5-7.8)**	**1.5**	**15**	**2.6**

Variable	Signal CV (95% CI)	Noise CV (95% CI)	SNR	Mean	SD
Positive Impulse [Ns]	10.0 (9.0-13.9)	17.1 (15.6-22.0)	**0.6**	827	166
Positive Takeoff Impulse [Ns]	4.7 (4.3-6.6)	3.4 (3.1-4.4)	**1.4**	453	53
Takeoff Peak Force-BM [N.kg $^{-1}$] *	**5.8 (5.3-8.2)**	**4.0 (3.6-5.1)**	**1.4**	**26**	**2.8**
Braking Phase Duration-Concentric Duration [%]	8.5 (7.7-11.9)	7.0 (6.4-8.9)	**1.2**	114	16
Braking Phase Duration-Contraction Time [%]	4.3 (3.9-6.0)	6.0 (5.5-7.7)	**0.7**	42	4.9
CMJ Stiffness [N.m $^{-1}$] *	**12.2 (11.0-17.0)**	**7.1 (6.5-9.1)**	**1.7**	**6,100**	**1,332**
Contraction Time-Eccentric Duration [%] *	**3.5 (3.2-4.9)**	**1.7 (1.6-2.2)**	**2.1**	**159**	**6.4**
Eccentric Peak Power-Concentric Peak Power Ratio	12.8 (11.5-17.8)	12.5 (11.4-16.0)	**1.0**	0.5	0.1
Eccentric-Concentric Duration [%] *	**9.9 (8.9-13.8)**	**4.6 (4.2-5.9)**	**2.2**	**171**	**18**
Eccentric-Concentric Mean Force Ratio [%]	2.1 (1.9-2.9)	1.8 (1.7-2.3)	**1.2**	51	3.7
Flight Time [ms]	2.3 (2.1-3.2)	1.9 (1.8-2.5)	**1.2**	605	40
Flight Time-Contraction Time Ratio	4.4 (4.0-6.2)	3.7 (3.4-4.8)	**1.2**	0.8	0.1
Flight Time-Eccentric Duration Ratio *	**7.7 (6.9-10.7)**	**4.4 (4.0-5.6)**	**1.8**	**1.3**	**0.2**
Jump Height Flight Time [cm]	4.7 (4.2-6.5)	3.9 (3.6-5.0)	**1.2**	45.1	6.0
Jump Height Imp Mom [cm] *	**11.8 (10.7-16.5)**	**8.2 (7.5-10.5)**	**1.4**	**36.5**	**6.8**
Lower Limb Stiffness [N.m $^{-1}$] *	**13.1 (11.8-18.2)**	**7.5 (6.8-9.6)**	**1.7**	**5,791**	**1,352**
Mean Eccentric Concentric Power-Time [W.s $^{-1}$] *	**10.8 (9.8-15.0)**	**5.9 (5.4-7.6)**	**1.8**	**2,173**	**350**
Movement Start to Peak Force [s]	11.1 (10.0-15.5)	9.2 (8.4-11.8)	**1.2**	0.5	0.10
Movement Start to Peak Power [s] *	**5.1 (4.6-7.1)**	**2.7 (2.5-3.5)**	**1.9**	**0.7**	**0.10**
RSI modified [m.s $^{-1}$]	5.7 (5.1-7.9)	5.3 (4.9-6.9)	**1.1**	0.6	0.1
Total Work [J] *	**7.3 (6.6-10.2)**	**4.8 (4.3-6.1)**	**1.5**	**1,253**	**187**

* = non-overlap of 95% confidence intervals; RFD – rate of force development; RPD – rate of power development

Appendix 9: Variable descriptions

Composite Variables

Variable	Description
CMJ Stiffness	Peak force during take-off divided by displacement at the start of the concentric phase (countermovement depth)
Eccentric: Concentric Duration [%]	Ratio of eccentric to concentric duration as a percentage
Eccentric: Concentric Mean Force Ratio [%]	Ratio of mean forces over the eccentric and concentric phases as a percentage
Flight Time [ms]	Time from take-off to landing
Flight Time: Contraction Time	Ratio of the time spent in flight to contraction time
Jump Height (Flight Time) [cm]	Jump height calculated from flight time method
Jump Height (Imp-Mom) [cm]	Jump height calculated using impulse-momentum method
Lower-Limb Stiffness [N/m]	Change in vertical force divided by displacement of the centre of mass (countermovement depth) during the eccentric phase
Mean Eccentric + Concentric Power: Time [W/s]	Power during eccentric (converted to absolute values) plus concentric phases, divided by the total contraction time
Movement Start to Peak Force [s]	Time from start of movement to peak force
Movement Start to Peak Power [s]	Time from start of movement to peak power
RSI-modified [m/s]	Jump height (calculated by flight time method) divided by contraction time
Total Work [J]	Integrating the power-time curve from the start of movement through the concentric phase until the power output reaches zero
Peak Net Take-Off Force/ BM [N/kg]	Peak net (above bodyweight) force experienced during contraction (eccentric + concentric phases), relative to bodyweight
Take-Off Peak Force/ BM [N/kg]	Peak force during contraction (eccentric + concentric phases), relative to body mass
Vertical Velocity at Take-Off [m/s]	The vertical velocity at the instant of take-off

Eccentric Variables

Variable	Description
Eccentric Duration [ms]	Duration of the eccentric phase (from start of movement to the start of the concentric phase)
*Eccentric Acceleration Phase Duration [s]	The time period from the start of movement to maximum negative velocity
*Eccentric Braking Phase Duration [s]	Time period from minimum force to the start of the concentric phase
*Eccentric Deceleration Phase Duration [s]	The time period from maximum negative velocity to zero velocity (start of concentric phase)
Minimum Eccentric Force [N]	Minimum force during the eccentric phase (start of the eccentric braking phase)
Eccentric Peak Force/ BM [N/kg]	Peak force over the eccentric phase relative to body mass
Force at Zero Velocity [N]	Combined force when velocity is zero (point of maximum negative displacement)
Eccentric Mean Braking Force [N]	Mean force during the eccentric braking phase (from minimum force to the start of the concentric phase)
Eccentric Mean Deceleration Force [N]	Mean force during the eccentric deceleration phase
Eccentric Braking RFD-100ms/ BM [N/s/kg]	Eccentric RFD calculated over the first 100ms of the braking phase relative to bodyweight
Eccentric Braking RFD/ BM [N/s/kg]	Eccentric RFD calculated from the initiation of the active (braking) phase to the end of the eccentric phase relative to body mass
Eccentric Deceleration RFD/ BM [N/s/kg]	Rate of force development calculated over the eccentric deceleration phase relative to body mass
Eccentric Unloading Impulse	Net impulse from the start of movement to the start of the deceleration phase
Eccentric Braking Impulse	Net impulse from the initiation of the braking phase through to the end of the eccentric phase
Eccentric Deceleration Impulse	Net impulse from the start of the deceleration phase through to the end of the eccentric phase
Eccentric Peak Power	Peak power during the eccentric phase calculated via bodyweight integration data
Eccentric Mean Power/ BM [W/kg]	Mean eccentric power relative to body mass
Eccentric Peak Velocity	Maximum negative velocity during the eccentric phase (velocity at the start of the eccentric deceleration phase)
Countermovement Depth [cm]	Depth at start of concentric phase (point of zero velocity) calculated via bodyweight integration data

*Acceleration and braking phases overlap from the point of minimum eccentric force until the point of maximum negative velocity. Braking phase is a composite of this overlap and deceleration phase (i.e., point of minimum eccentric force to the point of zero velocity). These names (i.e., unloading, acceleration, braking, yielding and deceleration) are attempts to describe the muscle action on the centre of mass as it travels downward in the eccentric phase. In strict biomechanical terms, the force being created has a negative (downward) vector (direction) and the muscle action (i.e., eccentric) is specific to creating forces while muscle tissue lengthens. Thus, when considered fully, these names are not arbitrary insofar as they are linked to certain temporal markers, but helpful in informing the practitioner considering them as to the specific neuromuscular underpinnings of the kinetic analysis.

Concentric Variables

Variable	Description
Concentric Duration [ms]	Duration of the concentric phase (from the point of zero velocity to the point of take-off)
Concentric Peak Force/ BM [N/kg]	Peak force achieved during the concentric phase, relative to body weight
Concentric Mean Force/ BM [N/kg]	Average force produced throughout the concentric phase, relative to body mass
Concentric Impulse [Ns]	Total net impulse (above body-mass) from concentric start to take-off
Concentric Impulse-50ms [Ns]	Total net impulse (above body-mass) over the first 50ms of the concentric phase
Concentric Impulse-100ms [Ns]	Total net impulse (above body-mass) over the first 100ms of the concentric phase
P1 Concentric Impulse [Ns]	Net impulse (above body-mass) during the first 50% (timewise) of the concentric phase
P2 Concentric Impulse [Ns]	Net impulse (above body-mass) during the second 50% (timewise) of the concentric phase
Concentric Peak Power/ BM [W/kg]	Peak power achieved in the concentric phase, relative to body mass
Concentric Mean Power/ BM [W/kg]	Average power produced throughout the concentric phase, relative to body mass
Concentric RPD/ BM [W/s/kg]	Rate of power development from the start of the concentric phase to peak power relative to body mass
Concentric RPD-50ms/ BM [W/s/kg]	Rate of power development for 50ms from the start of the concentric phase relative to body mass
Concentric RPD-100ms/ BM [W/s/kg]	Rate of power development for 100ms from the start of the concentric phase relative to body mass
Concentric Peak Velocity [m/s]	Peak velocity achieved during the concentric phase
Velocity at Peak Power [m/s]	Vertical velocity at the point of peak power

Landing Variables

Variable	Description
Jump Height Relative Landing RFD [N/s/cm]	Landing rate of force development divided by jump height (calculated by flight time)
Jump-Height Relative Peak Landing Force [N/cm]	Peak force in landing divided by jump height (calculated by flight time)
Landing Net Peak Force/ BM [N/kg]	Landing net (above body mass) peak force relative to body mass
Landing RFD [N/s]	Landing rate of force development
Mean Landing Power [W]	Mean power of landing
Peak Landing Force/ BM [N]	Peak force on landing relative to body mass
Peak Landing Power [W]	Peak power of landing
Peak Landing Velocity [m/s]	Peak velocity of movement post landing

Appendix 10: Ethics approval

Subject: Your ethics application has been approved as low risk - ETH19-3614
Date: Tuesday, 9 June 2020 at 06:27:57 Irish Standard Time
From: research.ethics@uts.edu.au
To: Aaron Coutts, David Howarth
Attachments: Ethics Application.pdf

Dear Applicant,

Re: ETH19-3614 - "Quantifying neuromuscular performance of elite rugby union players: measurement characteristics and moderating factors"

Your local research office has reviewed your application and agreed that it now meets the requirements of the National Statement on Ethical Conduct in Human Research (2007) and has been approved on that basis. You are therefore authorised to commence activities as outlined in your application, subject to any conditions detailed in this document.
You are reminded that this letter constitutes ethics approval only. This research project must also be undertaken in accordance with all UTS policies and guidelines including the Research Management Policy.
Your approval number is UTS HREC REF NO. ETH19-3614
Approval will be for a period of five (5) years from the date of this correspondence subject to the submission of annual progress reports.
The following standard conditions apply to your approval:

- Your approval number must be included in all participant material and advertisements.
- Any advertisements on Staff Connect without an approval number will be removed.
- The Principal Investigator will immediately report anything that might warrant review of ethical approval of the project to the Ethics Secretariat (Research.Ethics@uts.edu.au).
- The Principal Investigator will notify the UTS HREC of any event that requires a modification to the protocol or other project documents, and submit any required amendments prior to implementation. Instructions on how to submit an amendment application can be found here.
- The Principal Investigator will promptly report adverse events to the Ethics Secretariat. An adverse event is any event (anticipated or otherwise) that has a negative impact on participants, researchers or the reputation of the University. Adverse events can also include privacy breaches, loss of data and damage to property.
- The Principal Investigator will report to the UTS HREC annually and notify the HREC when the project is completed at all sites.
- The Principal Investigator will notify the UTS HREC of any plan to extend the duration of the project past the approval period listed above through the progress report.
- The Principal Investigator will obtain any additional approvals or authorisations as required (e.g. from other ethics committees, collaborating institutions, supporting organisations).
- The Principal Investigator will notify the UTS HREC of his or her inability to continue as Principal Investigator including the name of and contact information for a replacement.

This research must be undertaken in compliance with the Australian Code for the Responsible Conduct of Research and National Statement on Ethical Conduct in Human Research.

You should consider this your official letter of approval.

If you have any queries about this approval, or require any amendments to your approval in future, please do not hesitate to contact your local research office or the Ethics Secretariat.

Ref: 12a

Appendix 11: Evidence of research integrity modules

UTS

UNIVERSITY OF TECHNOLOGY SYDNEY

Graduate Research School

Research Integrity for Students

Certificate of Completion

This is to certify that

David Howarth

has successfully completed

Module 1: Research Integrity and Code of Conduct

Production Note:
Signature removed prior to publication.

Professor Lori Lockyer,
Dean, Graduate Research School

University of Technology Sydney

Date: 16/02/2018

UTS
UNIVERSITY OF TECHNOLOGY SYDNEY

Graduate Research School

Research Integrity for Students

Certificate of Completion

This is to certify that

David Howarth

has successfully completed

Module 2: Plagiarism and Misconduct
Module 3: Risk Assessment
Module 4: Risk Management and Health & Safety
Module 5: Project Management

Production Note:
Signature removed prior to publication.

Professor Lori Lockyer,
Dean, Graduate Research School

University of Technology Sydney

Date: *16/02/2018*