Diagnostic measures to inform training prescription to alter countermovement jump strategy and improve performance

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I, Darius Bryce Sangari (student number: 14045975), affirm that this thesis is my own original work and the data presented in this thesis was obtained myself. Any external contributions have been appropriately credited and cited as per departmental guidelines.

I understand and acknowledge the principles of academic integrity, including the concept of plagiarism. I am fully aware of the university's policy and the consequences associated with it.

I submit this thesis for the degree of Doctor of Philosophy in Biomechanics at the University of Pretoria. I declare that this thesis is original and contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma at this or any other tertiary or educational institution.

Darius Bryce Sangari
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Abstract

Diagnostic measures to inform training prescription to alter countermovement jump strategy and improve performance

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Jumping is a fundamental demonstration of lower-body power across various sports, where the ability to generate maximal force quickly is crucial. Central to optimising vertical jumping performance is the stretch-shorten cycle (SSC), which involves the coupling of eccentric and concentric muscle actions with a rapid transition period. This cycle allows for the storage and release of elastic energy, enhancing force production in activities like the countermovement jump (CMJ). However, traditional measures of CMJ performance, such as jump height, often overlook the intricacies of how effective an athlete is at utilising the SSC mechanism.

Recent research emphasises the importance of analysing jump strategy – how an athlete moves their centre of mass (COM) during the CMJ – metrics derived from ground reaction force (GRF) data to understand and improve SSC utilisation. Despite this, challenges persist in assessing the variability and influence of these metrics on CMJ performance. Moreover, while lower-body strength is known to enhance CMJ performance, its relationship with jump strategy is less understood. This thesis aims to evaluate jump strategy metrics, investigate the influence of lower-body physical characteristics, and test the effects of a training intervention on jump strategy and CMJ performance.

The first study explores the variability and consistency of CMJ performance and jump strategy metrics, revealing the need for careful metric selection and interpretation. The second study examines the relationship between eccentric phase biomechanical parameters and CMJ performance, highlighting the importance and influence jump strategy has on optimising measures of CMJ performance. The third study investigates the influence of timing of peak GRF during the CMJ and maximal strength on jump strategy and CMJ performance, showing that stronger athletes achieve better performance outcomes and that the combination of increased strength and an optimised jump strategy produces the best CMJ performance outcomes. The final study of this thesis includes a six-week training intervention, which assess the impact of assisted CMJ exercises on jump strategy and performance. Despite changes in jump strategy metrics, no significant performance improvements were observed, suggesting that increased strength may be necessary to benefit from altered jump strategies.

This research provides insights into the complex interactions between jump strategy, SSC utilisation and lower-body strength, offering practical implications for optimising CMJ performance. The findings underscore the importance of holistic metric analysis and strength development in enhancing jump performance outcomes, paving the way for further research and refined training methodologies.

Supervisors: Helen Bayne and John Cronin

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List of Publications

Journal articles:

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Sangari DB., Cronin JB., Bayne H. Attenuated eccentric loading elicits changes in countermovement jump strategy. J Strength Cond Res. (In review)

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Sangari DB., Cronin JB., Bayne H. The influence of maximal isometric strength on countermovement jump performance and strategy. 28th Annual conference of the European College of Sports Science. 2023 July 4-7; Paris, France.

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Abbreviations

Item	Explanation
1RM	One repetition maximum
ANOVA	Analysis of variance
BW	Bodyweight
CMJ	Countermovement jump
COM	Centre of mass
CV	Coefficient of variation
D_{ecc}	Downwards displacement
DJ	Drop jump
DSI	Dynamic strength Index
F_{0V}	Force at zero velocity
F_{con}	Concentric peak force
F_{ecc}	Eccentric peak force
F_{min}	Minimum eccentric force
GRF	Ground reaction force
$I_{braking}$	Braking impulse
ICC	Intraclass correlation coefficient
I_{con}	Concentric impulse
I_{ratio}	Impulse ratio
ISQ	Net peak force during isometric squat
ISQ_{PF}	Maximum isometric force
P_{con}	Concentric mean power
PEC	Parallel elastic component
P_{ecc}	Eccentric mean power
P_{ratio}	Power ratio
RSI_{mod}	Modified reactive strength index
SEC	Series elastic component
SJ	Squat jump
SSC	Stretch shorten cycle
TO_p	Take-off momentum
T_{PF}	Timing of peak force
TTT	Time to take-off
V_{con}	Concentric peak velocity
V_{ecc}	Eccentric peak velocity
V_{TO}	Take-off velocity
W_{con}	Concentric work
W_{ecc}	Eccentric work
W_{ratio}	Work ratio

Chapter 1: Introduction

1.1 Background

Jumping is the simplest demonstration of lower-body power and is an inherent skill across various sporting disciplines (1). The ability to generate maximal force in minimal time is a key determinant of jumping performance (2). Central to understanding and enhancing this performance is the concept of the stretch-shorten cycle (SSC), which describes the coupling of eccentric (lengthening) and concentric (shortening) muscle actions, with a rapid transitional period named amortisation between the two actions. The SSC allows for storage of elastic energy during the active lengthening period (pre-stretch), which contributes to greater initial concentric force production (SSC preload) upon shortening (3, 4). This storage and release of energy results in improved performance in activities such as the countermovement jump (CMJ), compared to vertical jumps performed from static positions (e.g. squat jump) (3). However, an extended amortisation period may cause the stored elastic energy to dissipate as heat and reduce the performance-enhancing effects of the SSC (5). While the CMJ is a popular and valid test to assess lower-body power and neuromuscular fatigue (6), traditional performance measures such as jump height do not capture the nuances of an athlete's ability to utilise the benefits of the SSC.

Recent research has highlighted the importance of analysing jump strategy – the manner in which an athlete moves their centre of mass (COM) throughout the CMJ – to better understand the requirements for optimal jump performance (7). Diagnostic measures, which encompass a range of jump strategy metrics and measures of CMJ performance, may be derived from ground reaction force (GRF) data collected using force platforms. These metrics can provide information regarding an athlete's ability and jump execution in areas such as; magnitude of bodyweight unloading, phase-specific quickness, displacement of their COM, and GRF generation capabilities (7, 8). Analysis of jump strategy metrics can also offer deeper insights into how effective an athlete is at utilising the SSC mechanism during jumping tasks. However, the use of diagnostic measures to assess SSC ability and CMJ performance presents several challenges. There is currently an inadequate amount of information to discern the variability of these metrics, which limits the level of certainty with which they can be used to assess and monitor SSC ability and jump strategy. Another challenge that practitioners face in using jump strategy metrics is that their influence on CMJ performance is not fully understood, as few studies have investigated their direct correlations to measures of CMJ performance. These challenges exist as jump strategy is a relatively novel topic and thorough research has yet to be conducted. Insights into these challenges would allow practitioners to not only recognise the value of monitoring jump strategy metrics and their relationship with CMJ performance and SSC ability, but also to interpret change appropriately by understanding the variability of the metrics.

In addition to the SSC, lower-body strength plays a crucial role in determining CMJ performance. Greater lower-body strength enables athletes to generate higher levels of GRF during the CMJ, which contributes towards increased concentric impulse and, ultimately, jump height (9). Although the associations between maximal strength and jump performance are well documented (2), the associations between maximal strength and jump strategy are relatively unknown. Interestingly, previous investigators have reported associations between maximal strength and initial power and GRF production, suggesting that stronger individuals generate greater SSC preload during the CMJ (10, 11). This finding is of particular interest to the authors because a peak GRF occurring during amortisation, or early in the concentric phase of the CMJ, could indicate that hysteresis was minimised and the SSC mechanism was utilised effectively (12, 13). However, the associations between maximal strength and timing of peak GRF on jump strategy and CMJ performance are scarce. It would be beneficial for practitioners to understand the influence of the aforementioned associations, as it would help them to identify specific training requirements for individual athletes.

Changes in jump strategy metrics as a result of training interventions have been previously reported, indicating the potential for modifiable enhancements. Through implementation of high-intensity resistance and ballistic exercise training modalities, researchers have observed changes in jump strategy metrics characterised by greater unloading of bodyweight, increased eccentric peak force (a proximally similar metric to SSC preload) and an earlier shift in the occurrence of peak GRF, while simultaneously reporting improvements in CMJ performance (11, 14-16). Although the authors partially attributed increases in jump performance to changes in jump strategy metrics (11, 14-16), it is unclear which of the training modalities (resistance or ballistic exercises) were responsible for these changes. Another study, using a single training modality intervention, reported significant changes in jump strategy (specifically downwards displacement of the COM); however, the number of metrics included in the investigation did not provide a comprehensive analysis of jump strategy (17). Understanding how specific training influences jump strategy and CMJ performance is vital for practitioners, as it allows them to efficiently prescribe exercises best suited to the specific needs of their athletes.

1.2 Motivation and purpose

The motivation behind this research stems from the ongoing pursuit within the field of sports science to enhance athletic performance through deeper understanding of biomechanical parameters governing human movement. Understanding and optimisation of lower-body power, particularly in jump activities, are paramount in various sporting disciplines. The SSC plays a central role in enhancing jump performance; however, discrepancies exist in assessing an athlete's ability to utilise the SSC effectively, particularly in the context of jump strategy metrics derived from GRF data. These metrics offer insights into an athlete's ability to unload their bodyweight, generate GRF and optimise the SSC mechanism, yet their variability and validity to do so remains unclear due to limited research. Furthermore, the interaction between jump strategy and maximal strength is relatively unknown, despite maximal strength playing an underpinning role in improving athletic performance. Understanding these interactions and how training interventions can be used to influence jump strategy is crucial for practitioners to tailor training prescriptions effectively. This thesis intends to address these knowledge gaps, providing practitioners with the insights necessary to enhance athlete performance through informed training interventions.

1.3 Aim

The aim of this study was to evaluate alternative measures of SSC utilisation, investigate the influence of lower-body physical characteristics, and test the effect of a training intervention informed by traditional and novel diagnostic measures to improve countermovement jump strategy and performance.

1.4 Objectives

To achieve the aim of this investigation, the research was divided into the six objectives listed below:

1) To determine the reliability of jump strategy metrics derived from ground reaction force data during the CMJ.

2) To determine the consistency of jump performance metrics during the CMJ.

3) To investigate the relationship between eccentric-phase jump strategy parameters and CMJ performance.

4) To determine the relationship between timing of maximum peak force on eccentric-phase jump strategy parameters and measures of CMJ performance.

5) To determine the relationship between lower-limb strength on jump strategy metrics and CMJ performance.

6) To evaluate the effects of a training intervention programme, designed based on the results of the series of studies addressing objectives 1 to 5, to improve CMJ strategy and performance.

1.5 Context and methodology

The aforementioned objectives are addressed over the course of four investigations using statistical methodologies. Chapter 3 assesses the variability of CMJ performance measures and jump strategy metrics used in the surrounding literature, while Chapters 4 and 5 seek to determine the relationship between jump strategy variables, maximal strength, timing of peak force production and CMJ performance through cross-sectional analysis. Chapter 6 reflects on the findings of Chapters 3 to 5 to develop a training intervention aimed at improving CMJ performance over a longitudinal study design. The University of Pretoria delivers sports science support to a wide variety of sporting disciplines, including rugby, netball, hockey, swimming and athletics. The offered support includes monitoring athletes using biomechanical tools such as force platforms, upon which the CMJ and isometric squat (used to assess lower-body strength) tests are performed. The kinetic and kinematic data collected using software (Forcedecks, Australia) from these assessments is analysed in each experimental investigation to satisfy the outlined objectives within each chapter. This series of research studies was therefore influenced by practitioners’ questions and has directly contributed to the application of strength and power testing in this environment.

1.6 Outline and structure

The following chapters are presented as a series of articles, each designed to stand alone as an independent study (Figure 1.1). As a result, some repetition of content is inevitable, ensuring that each chapter can be read and understood in isolation without requiring reference to the other chapters.

1.6.1 Chapter 2

A review of literature relevant to the outlined objectives is presented in Chapter 2 to provide context for the following experimental chapters. The literature review briefly discusses the theories and mechanisms that allow for the performance enhancement benefits of the SSC. Furthermore, information regarding the current methods of quantifying SSC ability and jump performance is detailed. The review then elucidates kinetic and kinematic metrics that have previously been investigated for their variability and potential to inform on jump strategy and jump performance. A brief overview of CMJ modality (the shape of the force-time series created during the CMJ) is conducted to provide context to the rationale behind the interest in timing of peak force. Following this, information regarding the influence of maximal strength on athletic performance and its interaction with the SSC is presented. Finally, the impact that previous training interventions have had on jump strategy is discussed.

1.6.2 Chapter 3

Chapter 3 aims to determine the variability and consistency of alternative diagnostic measures. Employing statistical methods such as the intraclass correlation coefficient and coefficient of variation, the study examines within- and between-session variability. This analysis provides insights into the absolute and relative consistency of jump strategy metrics of interest, which is essential knowledge for interpreting differences between athletes and change over time.

1.6.3 Chapter 4

In Chapter 4, the relationships between eccentric-phase jump strategy metrics and CMJ performance measures are determined. Through a comprehensive examination employing correlational and linear regression analyses, the study aims to validate the metrics of interest by elucidating their impact on CMJ performance. The findings of this chapter contribute to a deeper understanding of the jump strategy factors driving superior jump performance.

1.6.4 Chapter 5

In this chapter, the associations between maximal strength and timing of peak GRF on jump strategy and CMJ performance are investigated. Adopting a cross-sectional design, this experiment attempts to provide a deeper understanding of how variations in strength and timing of peak GRF influence jump strategies and, ultimately, jump performance.

1.6.5 Chapter 6

The last experiment of this thesis assesses the effectiveness of a targeted training intervention program on jump strategy metrics and CMJ performance. Drawing on the insights gathered from the preceding chapters, this chapter requires a longitudinal research design to determine the efficacy attenuated eccentric loading protocol thereby bridging the gap between theory and practical application.

1.6.6 Chapter 7

The final chapter of this thesis presents a cumulative overview of the experimental research conducted. The findings from the experimental chapters are discussed within the context of the surrounding literature. In addition, the strengths and limitations of this thesis and a brief review of the practical implications of the main findings are presented.

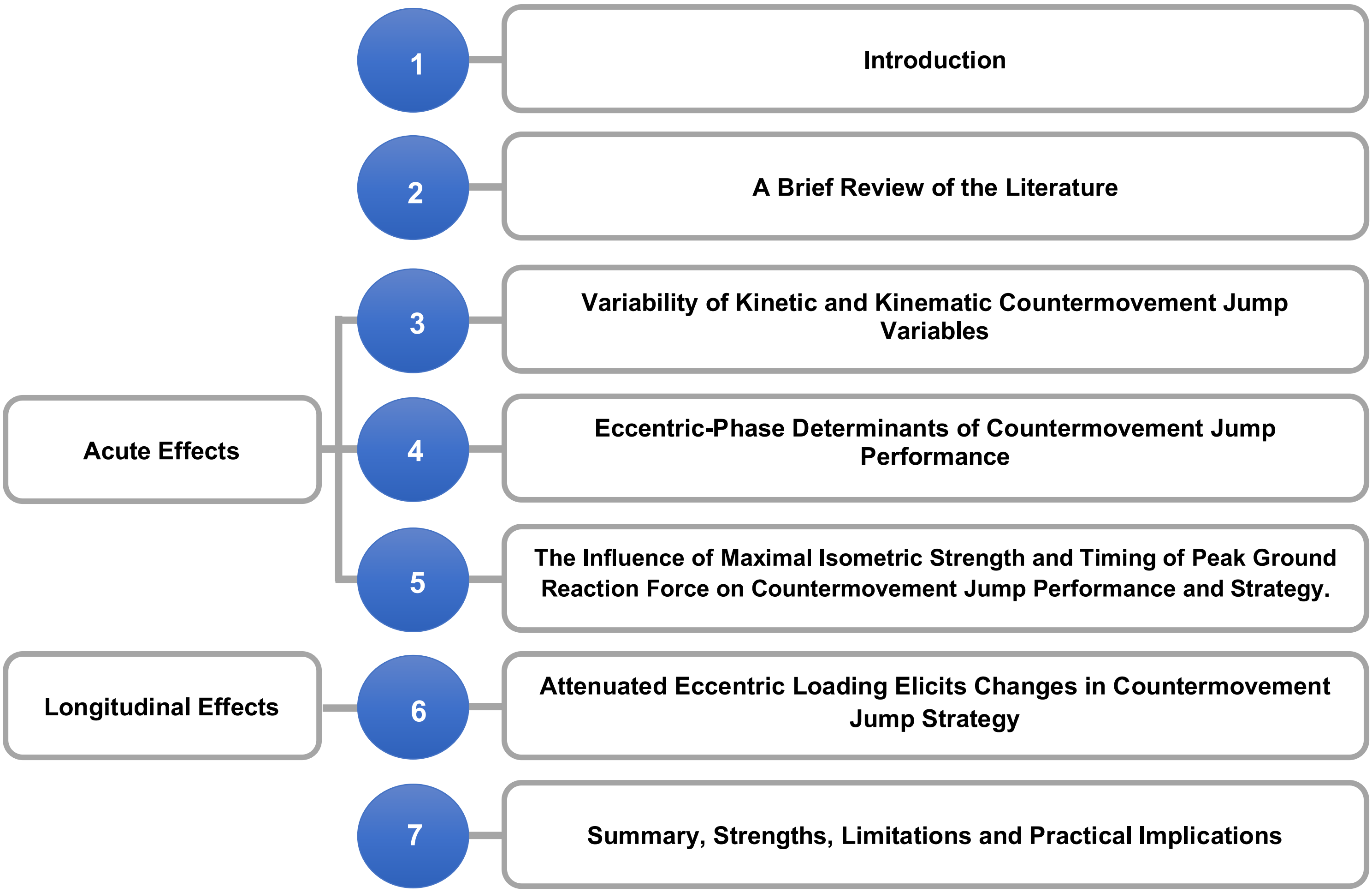

Figure 1.1 Thesis Structure

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Chapter 2: Review of the Literature

2.1 Introduction

The stretch-shorten cycle (SSC) describes the coupling of eccentric (lengthening) and concentric (shortening) muscle actions and is common in sporting movements such as sprinting, jumping and throwing (1). The SSC is a performance enhancing mechanism with benefits that can be observed by comparing the jump performances between a concentric-only squat jump (SJ) and an SSC countermovement jump (CMJ) (2). Jump height from a CMJ is typically greater than that from an SJ because the countermovement or eccentric muscle action (pre-stretch) prior to concentric muscle action augments performance as compared to the SJ, which is not immediately preceded by a pre-stretch (2). This review aims to summarise the literature surrounding the mechanisms of the SSC and how its performance-enhancing effects have been assessed through CMJ performance. Furthermore, it will explore details regarding the influence and variability of kinetic and kinematic metrics (derived from the force-time series of a CMJ) on CMJ and SSC performance. Finally, this review will examine the impact of muscular strength and training interventions on kinetic and kinematic variables, the SSC, and CMJ performance.

2.2 The stretch-shorten cycle

There are several mechanisms that explain the aforementioned SSC augmentation; however, morphological and neurophysiological models are recognised as the two main contributing mechanisms and are discussed briefly (1, 2).

2.2.1 Morphological model

The morphological model relates to the structures responsible for the storage and utilisation of elastic energy. During the pre-stretch, elastic strain energy is stored as kinetic or strain energy in the muscle sarcomere (including myosin cross-bridges, z-discs, sarcolemma, sarcoplasmic reticulum and titin filaments), and within the endomysium, perimysium and epimysium that collectively form the parallel elastic component (PEC). The energy from these structures is transmitted to the tendon (including aponeuroses), otherwise known as the series elastic component (SEC) (3) to produce movement. Both PEC and SEC are capable of absorbing and storing elastic energy simultaneously, which can then be reutilised and, under the right conditions, can augment concentric force production (2, 3). The total amount of elastic energy that the PEC and SEC can store is difficult to assess; however, it is thought to be determined by the quantity (cross-sectional area of the muscle tendon units) and quality (orientation and composition of collagen fibres) of the elastic structures (4). The magnitude of stored elastic energy during an SSC exercise is hypothesised to be proportional to the applied force and the deformation of the elastic structures (5, 6). It has been suggested that a more rapid pre-stretch over a shorter displacement would increase the tensile forces experienced by the SEC and PEC, thereby increasing storage of elastic energy (7, 8). Another requirement for effective use of the elastic energy is a rapid transition from eccentric to concentric movement, as hysteresis (where stored elastic energy can dissipate as heat) can occur if the transition is delayed or performed too slowly (9).

2.2.2 Neurophysiological model

The neurophysiological model involves three mechanisms that are considered important in explaining SSC augmentation: the stretch-reflex, the potentiation of contractile elements and building of an active state. The stretch reflex is activated when muscles are actively lengthened at a rapid rate and proprioceptors (muscle spindles) are excited and send signals to the spinal cord to initiate a contraction of the stretched muscles to prevent overstretching (10). Simultaneously, proprioceptors in tendons (Golgi tendon organs) are activated when there is tension in the connecting muscle, which sends inhibitory signals to the spinal cord and causes a relaxation response in the muscle to distribute the tension between the muscles and tendons (10). The stretch reflex has been previously described as an inherent autonomic defence mechanism to protect muscles and tendons from tearing or rupturing (11), but it can tolerate increased forces as the tendons and muscles become more conditioned through exercise (5, 10). Potentiation of CE refers to rate coding (the rate at which motor units are recruited), the number of motor units recruited, and motor unit synchronisation. This potentiation contributes less to the SSC enhancement than the storage of elastic energy (12, 13). The effects of the neuromuscular model are enhanced when these CE work in harmony by maximising each of their roles (rate of recruitment, number of motor units and timing of recruitment) (12, 13). As with the morphological model, it has been suggested that the velocity of the pre-stretch influences the number of motor units recruited and rate coding (7, 8). However, due to the force-velocity relationship of muscle contractions it takes time for muscles to generate large forces starting from a relaxed state (2, 5). The pre-stretch motion in SSC exercises (specifically during active lengthening) allows muscles time to build an active state and generate force prior to concentric muscle action (SSC preload), which contributes towards initial concentric force and impulse production and thereby improves jump performance (2, 14).

2.3 Countermovement jump metrics

2.3.1 Quantifying the SSC

Different methods have been introduced to quantify how effective a person is at utilising the SSC mechanism. Within the context of vertical jumping, the earliest method used to illustrate the benefits of the SSC was determined by subtracting the jump height recorded from a SJ from that of a CMJ (1). Later, the pre-stretch augmentation (PSA) was developed. PSA refers to SSC utilisation as a percentage difference in jump height between the CMJ and SJ and is calculated as [(CMJ-SJ)SJ-1]100 (15). The eccentric utilisation ratio (EUR) is a further approach that compares jump height and peak power differences between a CMJ and SJ as a ratio (16). The most recent method used when attempting to measure SSC utilisation is called the reactive strength index (RSI) and was developed as part of the Strength Qualities Assessment Test (SQAT) used in the Australian Institute of Sport (15). The RSI method was originally created in conjunction with the drop jump (DJ) test to observe an athlete’s ability to withstand and release stretch loads exhibited by the drop jump. It has since been adapted to be used in a CMJ test by dividing jump height by the time to take-off (from initiation of the jump to the moment of take-off) (17). This adaptation, named the modified reactive strength index (RSI_{mod}), has the potential to assess SSC utilisation (17, 18). These aforementioned methods quantify SSC utilisation through performance outcome measures rather than examining the kinetic and kinematic variables that are associated with pre-stretch and SSC preload, which could provide more specific information regarding SSC utilisation. Although other measures comparing eccentric to concentric kinetic variables (impulse, work, and power) as ratios have previously been experimented with, they provide limited information regarding storage and release of energy during the CMJ (19, 20).

2.3.2 Performance metrics

The CMJ is a reliable measure of lower-body power and neuromuscular status (21, 22). Jump height has been the predominant measure of jump performance; however, newer measures such as RSI_{mod} and take-off momentum (TO_p) have recently been introduced (17, 23). As mentioned previously, while RSI_{mod} was created as a measure of ballistic ability (the ability to generate maximal force within a short duration) (24), it does not provide information pertaining to how effective athletes are at storing and releasing elastic energy (17). As researchers use RSI_{mod} as a tool to monitor long-term performance of athletes, it may be that other practical applications for its use are identified in the future. The performance marker TO_p (calculated as a product of take-off velocity and body mass) was reported to be a valid, alternative measure to that of sprint momentum, which has been used to discriminate between performance levels of collision sport athletes (23). Additionally, TO_p can be used to monitor CMJ performance while considering within-athlete changes in body mass over time. Although these measures of jump performance provide information regarding athletic qualities, they fail to inform on how effective an athlete is at utilising the benefits of the SSC.

2.3.3 Kinetic and kinematic metrics

Investigators have become interested in examining the force-time series of a CMJ, as it provides information regarding an athlete’s jump strategy (25-27). The term ‘jump strategy’ refers to the manner in which an athlete moves their centre of mass (COM), throughout the eccentric and concentric phases of a CMJ (28) and can be examined through analysis of ground reaction force (GRF) data. This interest in jump strategy has grown from the evidence that suggests that eccentric movement indirectly influences jump performance through influencing concentric force production (2, 8). To further understand an athlete's jump strategy and neuromuscular function, the eccentric phase of a CMJ has been divided into two subphases: the unweighting phase (from the initiation of the CMJ until eccentric peak velocity - V_{ecc}) and the braking phase (from V_{ecc} until the moment COM velocity is equal to 0 m.s^{-1}) (Figure 2.1) (14, 29). The unweighting phase may be further subdivided into unloading (before minimum GRF) and yielding (after minimum GRF) phases (14). Variables such as minimum eccentric force (F_{min}), eccentric peak force (F_{ecc}), V_{ecc}, eccentric peak power (P_{ecc}), braking impulse (I_{ecc}), and downwards displacement (D_{ecc}) provide valuable information regarding pre-stretch and jump strategy (1, 7). Another variable that has recently gained interest is force at zero velocity (F_{0V} – GRF at concentric initiation), as it may provide a direct indication of SSC preload (8, 27, 30, 31). However, before investigating the validity of the aforementioned variables and their value for monitoring jump strategy, their variability needs to be quantified.

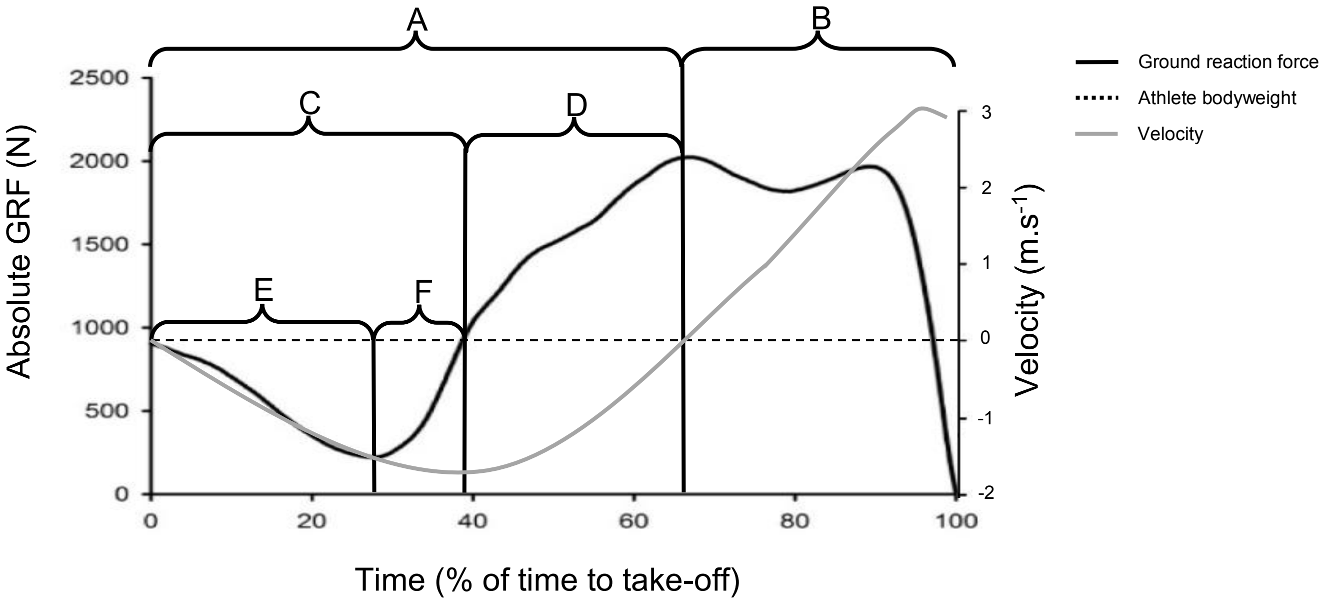

Figure 2.1 Force-time and velocity-time series of the countermovement jump. A = eccentric phase; B = concentric phase; C = unweighting phase; D = braking phase; E = unloading phase; F = yielding phase. Adapted from Lake and McMahon (28)

2.3.4 Variability of CMJ performance and jump strategy metrics

The absolute and relative variability, as measured by intraclass correlation coefficient (ICC) and coefficient of variation (CV) (respectively), of CMJ performance metrics and concentric-phase variables have previously been established. Jump height from a CMJ has consistently been reported to have acceptable (ICC > 0.67; CV < 10%) within- and between-session variability, which provides certainty when using jump height to monitor long-term changes in lower-body performance (22). Similarly, the research surrounding the variability of RSI_{mod} has indicated its acceptable within- and between-session variability (17, 28, 32-39). As previously mentioned, TO_p is a relatively new CMJ performance marker; however, researchers have recently reported acceptable within-session variability for TO_p (23, 28) and, due to the impulse-momentum relationship, TO_p likely has a similar between-session variability to (absolute net) concentric impulse (40). Concentric variables such as concentric impulse, peak velocity, peak force, mean power and peak power have consistently been reported to have acceptable within- and between-session variability across multiple investigations (32, 39-41). Previous authors have compared eccentric and concentric-phase parameters in the form of a ratio which may be indicative of how effective an athlete is at utilising the SSC mechanism. However, the variability of such variables has yet to be investigated.

With regards to eccentric-phase variables, jump strategy metrics (including V_{ecc}, I_{ecc}, D_{ecc}, F_{ecc}, F_{0V} and P_{ecc}) have previously been reported to have acceptable within- and between-session variability across investigations (32, 39-41). Two investigations have reported F_{min} to have unacceptable (ICC < 0.67; CV > 10%) between-session variability (42, 43). However, this may be due to the data not being analysed as relative net GRF but rather as absolute values, as two other research groups presented acceptable within-session variability for F_{min} when expressed as a percentage of/relative to total bodyweight (28, 44). Other factors that may contribute towards increased variability of eccentric-phase variables have previously been listed as follows: the use of arm swing (40), verbal instructions given to participants (36), athlete experience and/or familiarisation (34), and equipment used to measure CMJ force-time data (45). However, the variability of eccentric-phase variables has been less thoroughly investigated than concentric-phase or CMJ performance variables, indicating a need for a more comprehensive analysis. Additionally, given that the eccentric and concentric phases are interdependent during a CMJ, examining the ratio of eccentric to concentric variables could provide insights into SSC utilisation. Ratios involving power, work and impulse (19) between the phases may offer a more integrated understanding of elastic energy storage and release. Despite the potential value of these ratio measures, their variability has not been established.

2.3.5 CMJ force-time curves

As the interest in the force-time series of a CMJ has grown, some investigators have focused their attention on the shape of the force-time series during the concentric phase and its relationship with jump performance. It has been observed that two distinct shapes can be produced: unimodal (single GRF peak) and bimodal (double GRF peaks) (19). It must be noted that an athlete may not consistently produce the same distinct shape within a single testing session. Previous investigators, examining 15 male athletes across 10 CMJ trials, have reported that 60% of the athletes consistently produced a bimodal curve, whereas none consistently demonstrated unimodal curves (29). Although it is unclear why these curves occur, investigators have suggested that variations in countermovement depth may influence modality because an increase in the occurrence of bimodal curves has been observed during CMJs performed with a D_{ecc} larger than a self-preferred depth (36, 46). This finding illustrates the importance of selecting appropriate verbal cues or standardising D_{ecc} in accordance with the goal of the investigation when examining the force-time curve.

Researchers have yet to determine which modality is beneficial for CMJ performance. Kennedy and Drake (19) suggested that a bimodal curve represented an inefficient use of the SSC, although no significant differences in jump height (ES = 0.28) or RSI_{mod} (ES = 0.3) between modalities were observed in their investigation. Contrastingly, Peng et al. (46) reported large increases in jump height (ES = 1.49) and RSI_{mod} (ES = 1.09) for bimodal shaped curves compared to unimodal shaped curves. Other investigators further subcategorised unimodal (early and late) and bimodal (high-to-low or first peak dominant, symmetrical, and low-to-high or second peak dominant) curves based on the occurrence of peak GRF to compare CMJ performances (26, 27, 47). Guess et al. (26) analysed the force-time series of 394 collegiate athletes and concluded that athletes who demonstrated unimodal curves had the greatest jump height and RSI_{mod} while the poorest performing group displayed a low-to-high bimodal shaped curve. Bayne et al. (47) reported that RSI_{mod} and TO_p were greater in bimodal high-to-low and unimodal early groups compared to the other subcategories, where peak GRF was present later in the concentric phase. Finally, McHugh et al. (27) found no statistical differences in jump height (~2%) or RSI_{mod} (~13%) when comparing first and second peak dominant bimodal curves. More research is required to determine which modality represents the most effective CMJ performance; however, Bayne et al. (47) suggests that the timing of peak force (T_{PF}) may have a greater influence on jump performance than CMJ force-time modality (47).

2.3.6 Timing of peak force and SSC utilisation

When peak GRF coincides with the moment of transition between eccentric and concentric muscle actions (known as amortisation) it indicates a rapid transition between the two muscle actions, as net force is directly proportional to acceleration. With T_{PF} occurring at amortisation, hysteresis is limited and potentiation of the contractile elements is maximised, thus optimising the effects of the SSC mechanism. The differences in jump performance and jump strategy between athletes who generated peak GRF at amortisation and those who did not have been investigated (27). Investigators observed that athletes (n = 52) who generated peak force at amortisation had a significantly greater jump height (~4%) and RSI_{mod} (~10%) than the athletes who generated peak GRF later in the concentric phase (n = 48) (27). However, inferences that can be made about the differences between the two groups are limited, as the T_{PF} of the athletes who did not generate peak GRF at amortisation was not specified (as it could have occurred at any point in the concentric phase and possibly in the eccentric phase) (27). When examining the jump strategy variables between bimodal first and second peak dominant jumps in the aforementioned investigation, significantly lower F_{min} (~35%) and greater F_{0V} (~20%) were observed in the first peak dominant group (27). Similar observations were reported by Cormie et al. (8), who sought to determine the influences of ballistic power training and heavy resistance training on SSC function by monitoring jump strategy variables. Along with

10-14% increases in jump height, it was reported that peak GRF had occurred earlier in the force-time series for the intervention groups while performing a lower F_{min} and greater F_{0V} and V_{ecc} compared to the control group (after completing a 10-week intervention protocol) (8). This suggests that the manner in which the eccentric phase of the CMJ is performed may determine the T_{PF}.

2.3.7 Influence of eccentric strategy

There are two components of eccentric jump strategy that can be altered: amplitude (D_{ecc}) and velocity (V_{ecc}). The amount of unweighting (F_{min}) also influences that eccentric phase strategy because greater downwards acceleration increases the demands of the braking phase. Both amplitude and velocity during the eccentric phase relate to the pre-stretch theory, in which length of stretch (amplitude) and rate of stretch (velocity) influence SSC preload (2). Previous investigations have demonstrated that jump strategies that adopt faster V_{ecc} and/or larger D_{ecc} result in greater jump heights than strategies adopting slower V_{ecc} and/or shorter D_{ecc} do (31, 35, 48-50). When CMJs are performed with a shorter than self-selected D_{ecc}, jump height decreases, which may be due to athletes having less time to generate an active state and apply force during the concentric phase, thus decreasing concentric impulse (2, 51). The surrounding literature appears to support the idea that a self-selected D_{ecc} optimises jump height more effectively than a deeper than self-selected D_{ecc} due to the torque-angle relationship, which describes the interaction between contractile and elastic components that optimises power output (35, 52, 53). Recently, investigators have reported moderate correlations between F_{min} and jump performance, where a lower F_{min} is correlated with greater RSI_{mod} ($r = -0.45$ and -0.47) and TO_p ($r = -0.34$) (28, 53). A lower F_{min} would require greater braking GRF to decelerate the momentum of the COM, as I_{ecc} is equal to unweighting impulse (54), thus increasing SSC preload and F_{0V} (2, 8). As for T_{PF}, McHugh et al. (27) suggested that the metric F_{min} appears more important than D_{ecc} for optimising T_{PF}. It would then be suggested that athletes seeking to improve their jump strategy must unweight more and achieve higher downwards velocity while maintaining their preferred depth. However, in doing so they may require greater levels of strength to decelerate their COM and effectively transition towards concentric muscle action (55).

2.4 Strength, jump strategy and CMJ performance

Muscular strength is defined as the amount of force a group of muscles can exert, which is dependent on the muscle morphology and neuromuscular factors (56). The force-velocity relationship dictates that the amount of force a muscle group can generate and the duration for which it can apply force decreases as the velocity of the muscle contraction increases (57). The product of force and velocity is power, which is mechanical work done over time. The influence of maximal lower-body strength on jump height is well documented: greater maximum strength allows for greater power production which is associated with improved jump height (58, 59). Numerous adaptations associated with increased maximal strength are also beneficial for mechanisms associated with the SSC. For example, increases in maximal strength are associated with muscle hypertrophy (increased cross-sectional area, including muscle sarcolemma and muscle-tendon units), as well as increased collagen content and quality in tendons, therefore increasing the total capacity for storage of elastic energy (60). The neuromuscular benefits of increased strength not only offer increased contractile capacity (therefore allowing a greater degree of potentiation of the contractile elements) but also enhancement of the stretch reflex (61). In support of these adaptations, investigators have reported that stronger athletes are capable of greater power production early in the concentric phase (62), as well as a greater GRF (8, 63) than weaker athletes are. However, literature investigating the influence of maximum strength on SSC ability (and specifically the effects on jump or movement strategy variables) is scant.

Researchers have suggested that stronger athletes utilise distinctly different jump strategies to those of weaker athletes (7). Specific differences in the jump strategies of stronger and weaker athletes were reported by Cormie et al. (8) after an investigation aimed at determining the influence of ballistic versus resistance training on SSC ability. At baseline, there were no significant differences between stronger and weaker athletes in terms of F_{min}, V_{ecc} and D_{ecc}; however, F_{0V} was significantly greater in stronger athletes (8). McMahon et al. (41) compared two groups separated by low and high dynamic strength indexes (DSI), which is the ratio between CMJ concentric peak force and isometric mid-thigh pull peak GRF. The investigators reported greater relative maximal strength (as measured by isometric mid-thigh pull), V_{ecc}, and D_{ecc} in the low DSI group, while no significant differences were observed for F_{ecc} (measured within a similar temporal proximity to F_{0V}) (41). These investigations provide some evidence to suggest that jump strategy may be dependent on maximal strength; however, direct comparisons must be performed to fully elucidate the correlations between jump strategy and maximal strength.

2.5 Jump strategy and interventions

Training, whether through ballistic power or heavy resistance training (or both), has been found to induce significant changes in jump strategy (8, 64-68). Researchers monitoring changes in jump strategy (over four to 12 weeks) have reported similar findings, such as decreased F_{min} (8, 64-68) and increased V_{ecc} (8, 64, 66), F_{ecc} and F_{0V} (8, 65, 66), while some reported a shift in peak GRF (65, 67, 68), denoting an earlier occurrence of T_{PF}. These changes in jump strategy are desirable as they increase stored elastic energy in the SEC and PEC and induce greater potentiation of the contractile elements, which can potentiate force output during the concentric muscle action (69). These changes in eccentric jump strategy variables occurred in a relatively short period of time in most studies (between four and five weeks) (8, 66, 68, 70); however, the duration required for athletes to benefit from these changes and improve CMJ performance varies between investigations (8, 66, 67). It is suggested that the underpinning factor determining the rate at which CMJ performance improved as a result of changes in the eccentric force-time series is the relative maximal strength of the athletes (8, 67). Increases in F_{0V} were observed for both strong and weak athletes across multiple studies; however, stronger athletes were able to maintain GRF production throughout the concentric phase (thus increasing concentric impulse and, ultimately, jump height), while their weaker counterparts could not (8, 64, 66, 67). However, researchers conducting interventions over 10 to 12 weeks reported similar magnitudes of improvement between stronger and weaker athletes, which may be due to the weaker athletes increasing their relative strength over the course of the investigations (8, 71). One investigation reported a non-significant but practically relevant decrease (-7 kg back squat 1RM) in maximal strength in strong athletes over the course of the intervention, which corresponded to significantly improved (~14%)

jump height (8). This suggests that there might be a point of diminishing returns once a certain level of relative strength has been acquired or that the strong athletes may have further improved CMJ performance if they had maintained or increased their relative strength (8, 58).

2.6 Conclusion

This literature review provided a brief overview of the SSC and its impact on CMJ performance. The various metrics for quantifying the SSC, alongside analysis of the force-time series and jump strategy variables, highlights the complexity of evaluating CMJ performance. Previous attempts to quantify SSC utilisation present information with regards to jump performance, rather than providing sufficient information regarding storage and release of elastic energy during the CMJ. Although there remains ambiguity regarding which modality is most beneficial for CMJ performance, previous researchers have suggested that exploring T_{PF} could offer deeper insights into effective CMJ performance, jump strategies, and the SSC. The literature indicates that there may be a relationship between jump strategy and different levels of maximal strength, but a thorough exploration is required to clarify this distinction and understand how varying strength levels affect SSC ability. While changes in jump strategy due to interventions utilising ballistic power and resistance training modalities are discussed, it remains unclear which of the two training modalities was responsible for these changes. Identifying the exact mechanisms responsible for optimising jump strategy would be valuable for practitioners, as it would enable them to prescribe precise exercises that induce specific and desired adjustments in jump strategy to optimise the SSC.

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Chapter 3: Variability of Kinetic and Kinematic Countermovement Jump Variables

Abstract

The aim of this study was to quantify the absolute and relative variability of diagnostic measures of countermovement jump (CMJ) performance and jump strategy metrics. Ground reaction force data were collected from 25 female collegiate netball players on two occasions separated by 48 hours. Intraclass correlation coefficients (ICC) and coefficients of variation (CV) were used to determine the within- and between-session relative and absolute variability for each variable of interest respectively. Concentric-phase variables, including jump height and take-off momentum, were found to have small within- and between-session variability (ICC > 0.67 and CV < 10%). A mix of results was observed in eccentric-phase variables as kinematic variables were found to have less within- and between-session variability than kinetic variables. The impulse, power and work ratio metrics were found to have unacceptable within- and between-session variabilities (ICC < 0.67 and CV > 10%); however, the impulse ratio had small between-session variability. These findings provide a level of certainty to each of the CMJ performance and jump strategy metrics, as feedback for concentric variables can be provided to coaches and athletes immediately, while eccentric variables may require thorough analysis before being presented.

3.1 Introduction

Vertical jumps are often used by researchers and coaches to assess lower-limb ballistic performance and monitor neuromuscular function (1-4). The countermovement jump (CMJ) is the most common test used to quantify vertical jump height. A CMJ is performed by initiating a downwards countermovement before extending the hips, knees and ankles to jump vertically off the ground (5). Vertical jump height can be assessed using a range of equipment (such as contact mats, video analysis and accelerometers); however, force platforms have been considered the 'gold standard' tool as they enable mechanistic measures other than jump height to be quantified (6, 7). For example, force-time data allows for derivation of centre of mass kinematic parameters and a greater understanding of how the eccentric and concentric phases of a CMJ are performed (8). Practitioners analyse kinetic and kinematic variables to better understand the movement strategies athletes implement when performing CMJs (9-11). It has been observed that jump strategies can be influenced through training adaptions, as well as through verbal cues (9, 10). With the growing number of CMJ variables used to analyse different jump strategies and performances, it is important to understand the variability of all these measures to justify their use.

Concentric variables such as peak velocity, power and impulse were the primary focus of investigations analysing CMJ performance for many years (12). As jump height has been valued as the most useful and important measure of the CMJ (and is calculated from take-off velocity derived from net impulse) it would seem logical to analyse concentric-phase variables such as velocity, power, force and impulse due to their strength of association ($r > 0.70$; $p < 0.05$) (13-16). The absolute (coefficient of variation - CV) and relative (intraclass correlation coefficient - ICC) consistency of jump height and other concentric variables has previously been observed to have acceptable variability ($CV < 10\%$; $ICC > 0.67$). More recently, interest in eccentric variables has grown as changes in eccentric kinematic and kinetic variables (such as eccentric peak velocity, power, impulse and countermovement depth) have been observed to influence the behaviour of variables in the concentric phase, as well as jump performance (9, 11, 17). Previous authors have reported mixed results for eccentric-phase variables, suggesting that either more attention is given to the concentric portion of the CMJ by athletes or that the athletes with unacceptable variability have less control or consistency over their jump strategy (18-20). Although the variabilities of some eccentric-phase parameters have been investigated, they have not received as much attention (in terms of sample size, heterogeneity of participants, and quantity of investigations) as concentric variables have. It appears that the eccentric phase would certainly benefit from a more comprehensive statistical analysis with different samples and larger sample sizes.

Given that the eccentric and concentric phases do not happen in isolation in a CMJ, variables that look at the combination of the phases are of interest to the authors of this study. For example, the modified reactive strength index (RSI_{mod} - calculated by dividing jump height by time to take-off) was created to measure an athlete's "explosiveness" or ballistic ability. Although RSI_{mod} has been observed to have acceptable absolute and relative consistency (CV < 10%; ICC > 0.67), it does not provide descriptive information pertaining to either eccentric- or concentric-phase parameters (18, 21-24). A comparison between eccentric- and concentric-phase parameters (such as power, work and impulse) in the form of a ratio could potentially provide an indication of the storage and release of elastic energy exhibited during the stretch-shorten cycle (SSC). To the knowledge of the authors, however, the variability of such ratio measures has not been established. Therefore, the aim of this study was to quantify the absolute and relative consistency of eccentric and concentric kinetic and kinematic variables, as well as ratios that incorporate measures across different phases when performing the CMJ.

3.2 Materials and methods

3.2.1 Experimental design

To assess the consistency of kinetic and kinematic variables associated with CMJ performance, a repeated measures design was used to determine the within-session and between-session absolute and relative consistency. Countermovement jumps were performed on two occasions separated by 48 hours on dual force platforms. Force-time data were recorded, the variables of interest calculated and compared within and between testing occasions using measures of absolute (CV) and relative (ICC) consistency.

3.2.2 Participants

Twenty-five female collegiate netball players (age: 21 ± 1.7 yr, height: 1.76 ± 0.08 m, mass: 70.3 ± 8.0 kg) volunteered and provided informed consent to participate in this study, of whom 22 completed both testing sessions. None of the participants reported any injuries at the time of testing and all competed at a collegiate level of competition. Ethical approval was granted by Faculty of Health Sciences Research Ethics Committee (771/2020).

3.2.3 Procedures

Testing was conducted at the same time of day and participants were asked to wear the same footwear to each testing session. Both sessions began with the completion of a standardised dynamic warm up, including three sub-maximal CMJs with increasing intensity for each jump. All participants were familiar with the CMJ testing protocol and previously performed CMJs as part of a routine athlete-monitoring programme. Participants were asked to stand on the dual force platform (JM6090-06, Bertec, USA) with one foot on each plate. Participants stood still prior to initiating the first CMJ (to allow determination of body weight for post-testing analysis) and then performed three countermovement jumps (with between 30 and 60 seconds of rest between each jump) with their arms akimbo to eliminate the use of arm swing. Participants were instructed to “jump as high as possible, and as fast as possible” and to “maintain full extension during the flight phase until the moment of touchdown”. Countermovement depth was not controlled. A CMJ trial was repeated if the participant removed their hand/s from their hips when performing a CMJ, did not land on the platform with both feet, or tucked their legs during the flight phase.

3.2.4 Data collection and data analysis

Ground reaction force data was sampled at 1000 Hz and recorded using Forcedecks (Vald Performance, Australia) software. Force and time data were recorded for each trial and variables of interest were calculated from the force-time record (Table 3.1). Jump height was calculated using centre of mass take-off velocity, which was determined through the impulse-momentum method (25). The data recorded by Forcedecks were exported to a CSV file and additional calculations for take-off momentum, and power, impulse and work ratios were performed in Microsoft Excel (calculations described in Table 3.1). The interquartile rule was used to identify outliers for each variable per trial, relative to all trials for the whole cohort. Observations were considered outliers if they were lower than the first quartile minus 1.5 times the interquartile range, or higher than the third quartile plus 1.5 times the interquartile range. The statistical identification of the outliers was used to screen for possible erroneous data and trials were only excluded if multiple metrics within a trial were outliers. Participant datasets were removed if they had not completed both testing sessions.

CMJ phases were defined by previously established methods (21, 26). The first CMJ phase was the weighing phase, where the participant was asked to stand completely still on the force platforms for at least one second to record body mass and to correctly identify initiation of CMJ (26). The eccentric phase was divided into the unweighting and braking phases. The initiation of the unweighting phase was identified when the vertical force decreased by a threshold of 20 N less than the participant's body mass. The braking phase began from the moment after peak negative velocity to the moment COM velocity equalled zero (which coincided with the lowest depth of the countermovement). The concentric phase began when the participant's COM vertical velocity exceeded a threshold of 0.01 m.s^{-1} (26) and ended when the participant was no longer in contact with the force platform, indicating the transition to the the flight phase of the CMJ. A threshold of 30 N was used to determine both take-off and landing.

Table 3.1 CMJ variable descriptions

Variable	Unit	Description	Abbreviation
Jump height	cm	Maximum height of the COM derived from take-off velocity	
Time to take-off	ms	Time from the initiation of CMJ to the moment of take-off	TTT
Concentric peak velocity	$m.s^{-1}$	Peak velocity during the concentric phase	V_{con}
Force at zero velocity	N	Force when the COM velocity is < $0.01 m.s^{-1}$	F_{0V}
Modified reactive strength index	AU	Jump height in metres: time to take-off	RSI_{mod}
Concentric mean power	W	Average power during the concentric phase	P_{con}
Eccentric mean power	W	Average power during the eccentric phase	P_{ecc}
Power ratio	AU	Concentric mean power: eccentric mean power	P_{ratio}
Concentric impulse	N.s	Impulse during the concentric phase	I_{con}
Braking impulse	N.s	Impulse during the braking phase	I_{ecc}
Impulse ratio	AU	Concentric impulse: braking impulse	I_{ratio}
Concentric work	N.m	Work during the concentric phase	W_{con}
Eccentric work	N.m	Work during the eccentric phase	W_{ecc}
Work ratio	AU	Concentric work: eccentric work	W_{ratio}
Take-off velocity	$m.s^{-1}$	Velocity at take-off	V_{TO}
Take-off momentum	$kg.m.s^{-1}$	Momentum at take-off	TO_p
Concentric peak force	N	Peak force during the concentric phase	F_{con}
Eccentric peak force	N	Peak force during the eccentric phase	F_{ecc}
Unloading of bodyweight	N	Minimum force during the eccentric phase	F_{min}
Downwards displacement	cm	Maximum vertical downwards displacement of COM	D_{ecc}
Eccentric peak velocity	$m.s^{-1}$	Peak downwards velocity during the eccentric phase	V_{ecc}

AU = Arbitrary Unit

3.2.5 Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics (Version 27) for Windows. Data were presented as means and standard deviations to represent centrality and spread of data. Normality was assessed using the Shapiro-Wilk test and skewness and kurtosis values. Intraclass coefficient correlation (ICC) and 95% confidence intervals (CI) were calculated for within-session variability across three CMJ trials on both testing occasions, and the mean of the best two (based on jump height) trials in each session was used in the analysis of between-session variability. In both instances, a two-way mixed effects model and absolute agreement protocol was applied (27). An ICC greater than 0.67 was deemed as having small variability, while an ICC lower than 0.67 was deemed as having large variability (28-33). The CV was used to explore the absolute consistency and was calculated for each participant by dividing the standard deviation between the three trials and dividing it by the mean of the three trials, then multiplying the results by 100 to be presented as a percentage (28-33). The within-subject CVs were then averaged across participants and presented as a within-subject mean CV (28-33). A CV of less than 10% was deemed as having small variability (28-33). Interpretation of ICC and CV results together were as follows: an ICC < 0.67 and CV > 10% were deemed as having large variability; an ICC > 0.67 or CV < 10%, but not both, were deemed to have moderate variability and an ICC > 0.67 and CV < 10% were deemed to have small variability (28-33).

3.3 Results

Means and standard deviations for all CMJ variables of interest were presented in Table 3.2.

3.3.1 Concentric variables

All concentric variables were found to have small variability for within-session (CV = 2.2 – 4.9%; ICC = 0.83 – 0.94) and between-session (CV = 2.6 – 6.7%; ICC = 0.72 – 0.89) comparisons.

3.3.2 Eccentric variables

Variables that were found to have small within-session variability were V_{ecc}, F_{ecc} and D_{ecc}. Small variability was found for P_{ecc} (CV < 10%; ICC > 0.67) in the first testing session, but there was moderate variability in the second testing session (CV > 10%; ICC > 0.67). Moderate variability was found for I_{ecc} (CV < 10%; ICC > 0.67) in the first testing session, but large variability was found in the second testing session (CV > 10%; ICC < 0.67). Moderate within-session variability (CV > 10%; ICC > 0.67) was found for F_{min} and W_{ecc}. All eccentric variables were found to have small (CV < 10%; ICC > 0.67) between-session variability, with the exception of F_{min}, W_{ecc} and D_{ecc}, which were moderate.

3.3.3 Time-dependent variables

All time-dependant variables (TTT and RSI_{mod}) were found to have small within-session variability (CV < 10%; ICC > 0.67). The E-index and TTT were found to have moderate between-session variability (CV < 10%; ICC < 0.67) while RSI_{mod} had large between-session variability (CV > 10%; ICC < 0.67).

3.3.4 Ratio variables

The power, impulse and work ratios were found to have large variability for both testing sessions; however, the work ratio was observed to have moderate variability (CV > 10%; ICC > 0.67) for the second testing session. The I_{ratio} was observed to have small between-session variability (CV < 10%; ICC > 0.67), whereas the P_{ratio} and W_{ratio} were found to have moderate and large between-session variabilities (CV < 10%; ICC < 0.67 and CV > 10%; ICC < 0.67) respectively.

Table 3.2 Within-session variability of CMJ variables based on three trials per session and between-session ICC based on the mean of three trials

Variable	Session	Mean	SD	Within-session CV	Within-session ICC	95% CI	CV/ICC inference	Between-session CV	Between-session ICC	95% CI	CV/ICC inference
Concentric variables											
Jump height (cm)	1	23.9	4.84	4.93	0.93	0.72-0.97	Small	6.69	0.84	0.54-0.94	Small
	2	25.4	4.32	4.43	0.91	0.66-0.97	Small				
Peak velocity (m.s^{-1})	1	2.36	0.18	1.57	0.94	0.84-0.98	Small	2.81	0.86	0.64-0.94	Small
	2	2.40	0.15	1.95	0.84	0.72-0.95	Small				
Vertical take-off velocity (m.s^{-1})	1	2.15	0.22	2.48	0.91	0.84-0.96	Small	3.35	0.83	0.50-0.93	Small
	2	2.22	0.19	2.23	0.90	0.82-0.96	Small				
Take-off momentum (kg.m.s^{-1})	1	148	17.9	2.48	0.94	0.79-0.98	Small	3.33	0.89	0.63-0.96	Small
	2	153	16.6	2.23	0.94	0.76-0.98	Small				
Concentric peak force (N)	1	1545	193	3.24	0.88	0.71-0.95	Small	4.50	0.80	0.57-0.91	Small
	2	1546	180	3.70	0.86	0.69-0.94	Small				
Force at zero velocity (N)	1	1473	222	4.08	0.91	0.82-0.96	Small	5.02	0.82	0.62-0.92	Small
	2	1506	192	4.82	0.83	0.70-0.92	Small				
Concentric mean power (W)	1	1532	190	4.22	0.89	0.67-0.95	Small	5.28	0.72	0.43-0.87	Small
	2	1584	179	4.24	0.83	0.63-0.93	Small				
Concentric impulse (N.s)	1	149	17.8	2.37	0.94	0.82-0.98	Small	3.17	0.89	0.74-0.96	Small
	2	153	16.6	2.18	0.94	0.77-0.98	Small				
Concentric work (N.m)	1	442	54.0	3.23	0.87	0.75-0.94	Small	2.64	0.89	0.55-0.90	Small
	2	446	46.4	3.30	0.87	0.70-0.95	Small				
Eccentric variables											
Eccentric peak velocity (m.s^{-1})	1	1.07	0.19	7.22	0.75	0.50-0.89	Small	6.58	0.81	0.38-0.93	Small
	2	1.14	0.17	7.19	0.75	0.54-0.88	Small				
Eccentric peak force (N)	1	1482	224	4.12	0.89	0.79-0.95	Small	4.87	0.83	0.64-0.93	Small
	2	1513	192	4.81	0.82	0.66-0.97	Small				

Unloading of bodyweight (N)	1	308	112	13.8	0.87	0.75-0.94	Moderate	18.2	0.77	0.37-0.91	Moderate
	2	263	104	23.2	0.75	0.56-0.88	Moderate				
Eccentric mean power (W)	1	369	75.0	11.0	0.67	0.46-0.83	Moderate	6.99	0.81	0.53-0.93	Small
	2	392	64.2	8.85	0.71	0.47-0.86	Small				
Braking impulse (N.s)	1	40.6	11.9	15.4	0.69	0.48-0.85	Moderate	9.22	0.83	0.63-0.93	Small
	2	40.8	9.23	14.5	0.61	0.38-0.80	Large				
Eccentric work (N.m)	1	114	35.0	13.7	0.67	0.45-0.84	Moderate	10.6	0.79	0.76-0.95	Moderate
	2	119	28.6	10.0	0.72	0.49-0.86	Moderate				
Countermovement depth (cm)	1	29.0	5.35	8.10	0.73	0.29-0.90	Small	7.28	0.65	0.33-0.84	Moderate
	2	29.4	4.11	7.51	0.71	0.40-0.88	Small				
Time-dependent variables											
Time to take-off (ms)	1	825	133	5.79	0.79	0.62-0.91	Small	6.24	0.61	0.27-0.81	Moderate
	2	791	95.9	6.06	0.70	0.50-0.85	Small				
RSI_{mod} (AU)	1	0.31	0.08	8.62	0.90	0.80-0.95	Small	12.1	0.65	0.30-0.84	Large
	2	0.35	0.07	7.95	0.83	0.68-0.92	Small				
Ratio variables											
Power ratio (AU)	1	4.23	0.57	10.9	0.39	0.13-0.66	Large	7.54	0.59	0.25-0.81	Moderate
	2	4.12	0.56	11.0	0.51	0.20-0.75	Large				
Impulse ratio (AU)	1	3.89	1.04	13.4	0.63	0.39-0.81	Large	6.86	0.85	0.67-0.94	Small
	2	3.95	0.97	14.2	0.37	0.10-0.64	Large				
Work ratio (AU)	1	4.20	0.95	12.4	0.52	0.26-0.74	Large	10.6	0.62	0.28-0.82	Large
	2	3.95	0.76	9.47	0.60	0.35-0.79	Moderate				

3.4 Discussion

The aim of this study was to quantify the within- and between-session variability of eccentric and concentric kinetic and kinematic variables, as well as ratios that incorporate measures across different phases when performing the CMJ. The main findings were: 1) jump height and concentric-phase variables had small within- and between-session variability; 2) eccentric-phase variables were found to have larger variability than concentric-phase variables; 3) time-dependent variables such as TTT and RSI_{mod} were found to have small within-session variability, but moderate to large between-session variability; and 4) the power, work and impulse ratios were found to have large within-session variability; however, the I_{ratio} was observed to have smaller between-session variability than the P_{ratio} and W_{ratio}.

Jump height and concentric-phase variables (V_{con}, P_{con}, I_{con}, W_{con}, F_{0V}, V_{TO}, TO_p, F_{con}) were found to have acceptable consistency, being classified as having small within- and between-session variability. The observed variability (CV = 1.6 – 4.9% ; ICC = 0.84 – 0.94) for concentric-phase variables in this study align with findings (CV = 1.4 – 3.3% ; ICC = 0.88 – 0.99) from previous investigations (9, 12, 18-21, 34-37). This study has added evidence to the existing body of literature that supports TO_p and F_{0V} to have small within- and between-session variability (4, 20, 38-40). These findings instil confidence in TO_p and F_{0V} to be further investigated for their potential to monitor jump performance and neuromuscular status. The small variability observed for concentric variables across multiple studies enables practitioners to provide immediate feedback on concentric jump testing and identify the smallest worthwhile changes with reasonable certainty.

The eccentric variables analysed in this study (V_{ecc}, F_{ecc}, F_{min}, P_{ecc}, I_{ecc}, W_{ecc} and D_{ecc}) were found to have larger variability (CV = 4.1 – 23.2% and ICC = 0.61 – 0.89) than the concentric variables (CV = 1.6 – 4.9% ; ICC = 0.84 – 0.94), which aligns with the findings of previous authors (18-21, 41). The variability of eccentric variables may be dependent on the instructions given to participants on how to perform the CMJ. Studies that have incorporated urgency in their instructions ("jump as fast as possible") observed smaller variability for eccentric variables, whereas studies that emphasised maximising jump height reported moderate to large variability (18-21). This study used the former instructions and observed (mostly kinetic) eccentric variables to have moderate to large variability. It has been suggested that skilled jumpers are able to better manipulate their jump strategies by changing the eccentric components of the CMJ, which could explain the increases in variability for eccentric variables (20). Despite higher variability in the performance of the eccentric phase, concentric-phase mechanics and jump performance were quite consistent.

Most kinetic eccentric-phase variables assessed in this study (I_{ecc}, P_{ecc}, W_{ecc} and F_{min}) were found to be more variable than kinematic variables (V_{ecc} and D_{ecc}), with the exception of F_{ecc}. Conflicting observations pertaining to the variability of I_{ecc} and P_{ecc} have been reported, and the differences in these findings may again be due to the instructions issued in each experiment (18-21). Even though D_{ecc} was not standardised in this study, the self-selected D_{ecc} chosen by participants was observed to have small within- and between-session variability (CV < 10%; ICC > 0.67). Previous authors have observed that a self-selected jump strategy is associated with smaller variability for D_{ecc}, while participants who have been instructed to vary from their personal jump strategy have been observed to increase variability for D_{ecc} (9). The small within- and between-session variability for F_{ecc} was observed to have very similar results to those of F_{0V}. The similarities in variability between the two variables is mostly likely due to the proximity of each measure on the force-time curve (13). This study was the first to report the absolute and relative consistency for F_{min} as an absolute value, which may explain the observed moderate variability, as previous investigators reported small within-session variability for F_{min} relative to BW (42, 43). However, it was observed that the group mean force for F_{min} decreased from the first to the second testing session (-17.3%), while other performance measures such as jump height and RSI_{mod} improved by 5.9% and 9.3% respectively. Very little is known about the relationship between F_{min} and CMJ performance, and future researchers should consider exploring the relationships between eccentric variables, such as F_{min}, and CMJ performance.

Measures of CMJ performance that utilised a duration component (RSI_{mod} and TTT) were found to have small within-session variability, which is similar to the results of previous investigations (18, 20, 44). However, the moderate between-session variability for RSI_{mod} and TTT observed in this study is inconsistent with the literature (37, 45, 46). The mean jump height increased while TTT decreased from the first to the second testing session (by 5.9% and 4.2% respectively), which resulted in an increase of 9.3% in RSI_{mod}. Jump strategy has been observed to affect the outcome of RSI_{mod} where the participant alters the magnitude of V_{ecc} and/or D_{ecc} during the CMJ (9, 47, 48). In the current study, D_{ecc} remained relatively similar between the first and second testing sessions (1.2% increase in the group mean) and there was a 6.2% increase in V_{ecc}, thus reducing the duration of the eccentric phase and overall TTT. It may be suggested that RSI_{mod} could be used as an indicator of change in jump performance, but kinetic and kinematic variables should be inspected to further understand the changes in jump strategy. Since both components of RSI_{mod} (jump height and TTT) have been used to monitor neuromuscular status, further investigation into the relationship between RSI_{mod} and neuromuscular status (fatigue and readiness) may add value to RSI_{mod} as a performance measure (1, 4, 49).

The variability of ratio metrics that may be considered for indirect quantification of the storage and release of elastic energy (SSC utilisation) was also investigated in this study. The power and impulse ratios were found to have large variability (CV > 10%; ICC < 0.67) for within-session testing, while the work ratio was observed to have moderate to large variability (CV = 9.5 – 12.4%; ICC = 0.52 – 0.60). This may have been due to incorporating eccentric variables (mean power, impulse and work) that were already found to have moderate to large variability. Using eccentric kinematic variables with small variability (observed in previous investigations) may yield different results when analysing ratio variables (18, 34). The I_{ratio} was the only ratio to have small between-session variability (CV < 10%; ICC > 0.67) and could therefore be considered as a potential long-term measure of SSC utilisation. Jump height is a result of V_{TO}, which is calculated from concentric net impulse; using concentric impulse to quantify the concentric component of the SSC seems logical (25). Braking impulse could then be used to provide an indication of the stored elastic energy, and a ratio or comparison between braking and concentric impulse may yield new information regarding SSC utilisation. As no other study has compared eccentric to concentric impulse as a ratio it may be beneficial to investigate the relationship between I_{ratio} (or its constituent parts) and jump performance, as it may potentially provide new information regarding SSC utilisation.

A number of limitations were encountered in this study. Firstly, the number of testing sessions (2) conducted may not have been enough to identify if values were changing or plateauing, therefore affecting understanding of the real absolute and relative consistency of the measures of interest. Even though the two testing sessions were conducted 48 hours apart, an improvement in jump performance was observed. A third testing session conducted 48 hours after the second may have observed either a decrease, increase, or stabilisation in jump performance results, which would have allowed for a more in-depth analysis of the variability of kinetic and kinematic CMJ variables. Secondly, the homogeneity of the participants may have affected the statistics and certainly generalisability of the findings (i.e. the netballers who participated in this study represent a relatively small group of sub-elite athletes and different populations may yield different results). It is therefore recommended that future research into the variability of CMJ variables should consider using multiple testing occasions and a broad range of populations in their methodologies to ensure appropriate conclusions can be made.

3.5 Conclusion

The aim of this study was to investigate the within- and between-session variability of established and novel kinetic, kinematic and ratio CMJ variables. Concentric variables in this study were found to have small variability, which is consistent with previous investigations and can be used to provide immediate feedback regarding jump strategy. Eccentric variables were observed to have larger variability than concentric variables, suggesting that practitioners should conduct thorough analysis of eccentric-phase jump strategy variables when monitoring long-term changes in jump strategy. Eccentric kinematic variables, such as V_{ecc} and D_{ecc}, were observed to have small within- and between- session variability and can be used with certainty to provide feedback to athletes and monitor long-term changes in jump strategy.

The small within-session variability of RSI_{mod} and TTT are consistent with the literature; however, the moderate between-session variability of these measures does not align with the findings of previous research. When monitoring long-term jump performance, jump height should be used to indicate changes in jump performance due to its small between-session variability compared to RSI_{mod}'s large variability.

The power, work and impulse ratios were observed to have large within-session variability, whereas I_{ratio} was the only ratio to have small between-session variability. However, as none of the ratio variables had acceptable within- and between-session reliability, their use for diagnostics in the future is problematic. As such, and given the acceptable reliability of the contributing variables to the ratios, it is advised that these variables are analysed in isolation to further understanding of both storage and release of elastic energy. Future researchers intending to use eccentric and concentric variables to assess and monitor jump performance should be cognisant of using variables that are not stable across trials and testing occasions, as any interpretation of results may lead to inaccurate diagnoses and conclusions.

3.6 Chapter summary

This chapter has addressed objective 1: determine the reliability of jump strategy metrics derived from ground reaction force data during the CMJ and objective 2: determine the consistency of jump performance metrics during the CMJ in 25 female collegiate netball players. The findings revealed small within- and between-session variability for concentric variables. However, eccentric-phase variables (particularly kinetic variables) exhibited larger variability than concentric-phase variables did. These findings underscore the complex nature of eccentric-phase variables and their potential impact on overall jump performance. Building on these insights, the subsequent chapter delves deeper into the relationships between eccentric-phase jump strategy variables and CMJ performance outcomes. Moreover, ratio variables, aiming to quantify storage and release of elastic energy, displayed unacceptable variability (with the exception of the impulse ratio, which exhibited small between-session variability). Due to the overall variability of ratio metrics, their diagnostic use was discouraged. Instead, analysing individual variables in isolation was recommended for a comprehensive understanding of jump performance. Thus, the information gathered in Chapter 3 has provided a foundation for the subsequent chapters, investigating the influence of eccentric-phase variables on CMJ performance.

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Chapter 4: Eccentric-phase determinants of countermovement jump performance

Abstract

The aim of this investigation was to determine the relationships between eccentric-phase kinematic and kinetic parameters and countermovement jump (CMJ) performance. Vertical ground reaction force data during the CMJs were collected from 201 collegiate athletes from various sports. A Pearson correlation coefficient was used to determine the strength of association between eccentric-phase parameters and markers of CMJ performance (jump height, take-off momentum (TO_p) and modified reactive strength index (RSI_{mod})). A stepwise linear regression model was used to further investigate the eccentric-phase determinants of CMJ performance. The best predictor variables for jump height were countermovement depth (D_{ecc}), force at zero velocity (F_{0V}) and unloading of bodyweight (minimum eccentric force - F_{min}) for females and males ($R^2 = 0.26$ and 0.23 respectively). F_{0V} was the only predictor for RSI_{mod} ($R^2 = 0.52$) in female participants and the combination of F_{0V}, eccentric peak velocity (V_{ecc}) and D_{ecc} was the best predictor for RSI_{mod} ($R^2 = 0.53$) in male participants. The best predictor variables for TO_p were F_{min}, V_{ecc}, D_{ecc} and F_{0V} for both females and males ($R^2 = 0.31$ and 0.66 respectively). The combined findings of the correlation analysis and stepwise regression revealed that eccentric-phase parameters, particularly D_{ecc}, V_{ecc}, F_{0V} and F_{min}, are important jump strategy metrics for maximising jump performance.

4.1 Introduction

The countermovement jump (CMJ) is the most common and practical vertical jump test used by practitioners to assess jump ability and lower-body power (27). Markers of jump performance such as jump height, modified reactive strength index (RSI_{mod}) and take-off momentum (TO_p) are used to monitor changes in lower-body performance over time. Jump height provides valuable information regarding neuromuscular status, lower-body power and athletic performance (3). The RSI_{mod} has been suggested to indicate ballistic and reactive-strength ability, as it accounts for jump height relative to the time taken to complete the jump (7). The measure TO_p effectively scales jump performance to body mass and may be useful when comparing athletes of different sizes or assessing within-athlete changes when body mass varies over time (23). Researchers and practitioners have become interested in jump strategy – the manner in which an athlete moves their centre of mass (COM) through the different CMJ phases – as jump strategy can provide insight into an athlete's ability to unload bodyweight, phase-specific quickness and force-generation capabilities (12, 20). Insight into jump strategies can be obtained from analysing the force-time series data collected using force platforms (12).

The CMJ has commonly been divided into three phases: unweighting, braking and propulsion (26). The unweighting and braking phases are often categorised as the eccentric phase of the CMJ; however, researchers have argued that true "eccentric" neuromuscular function begins at minimum ground reaction force (GRF) during the unweighting phase (11). This argument has led to a subdivision of the unweighting phase into the unloading (before minimum GRF) and yielding (after minimum GRF) phases and has allowed researchers to gain a deeper understanding of an athlete's jump strategy and better monitor eccentric-phase training adaptations. The propulsion phase occurs from the initiation of the upwards movement until take-off, involving predominantly concentric muscle activity (26). The coupling of eccentric and concentric muscle contractions is common in sporting movements and is referred to as the stretch-shorten cycle (SSC) (35). The eccentric phase of the SSC elicits a performance-enhancing effect, as jump heights achieved during CMJs have been observed to be higher (by 18-30%) than those from concentric-only squat jumps (performed from a static start) (2). The SSC enhancement is theorised to be influenced by the storage of elastic potential energy (tendons and muscle sarcomere) and the activation of the stretch reflex (muscle spindles and Golgi tendon organs) (19). The contribution of increased force production prior to the initiation of the concentric phase (SSC preload), from both elastic energy and stretch reflex, are suggested to be influenced by the velocity and amplitude of the eccentric muscle action (pre-stretch) (2, 19).

In accordance with these SSC enhancement theories, jump strategies that adopt faster eccentric peak velocity (V_{ecc}) and larger countermovement displacements (D_{ecc}) have been observed to increase CMJ height, compared to strategies that utilise slower and smaller countermovement velocities and displacements (4, 8, 9, 31). A faster V_{ecc} would require greater deceleration demands during the braking phase if duration was unchanged, which would require larger GRF to be produced at the end of the descent (10, 33). In addition, larger D_{ecc} has been associated with larger braking impulse and eccentric peak forces (15, 17). Jump strategy metrics (specifically V_{ecc} and D_{ecc}) may therefore provide an indication of an athlete's ability to increase elastic energy storage and enhance jump performance. Previous investigations have compared jump strategies and jump performances between groups of athletes separated by level of jump ability (8, 24), sex (25), or different verbal instructions influencing amplitude and velocity (18, 31, 32). The studies that have investigated the direct associations between jump strategy and CMJ performance used either a loaded (17 kg Smith machine) CMJ test protocol (9) or recreational populations (12). Research identifying the strength of the direct associations between COM acceleration, velocity and displacement during the eccentric phase and CMJ performance outcomes is limited, and practitioners could benefit from understanding the influence of different eccentric-phase jump strategies on CMJ performance.

Researchers have observed that athletes producing larger braking impulse have increased concentric impulse and jump performance than those who generate less braking impulse (10, 33). The increased braking impulse may lead to increased force at zero velocity (F_{0V}), thus enhancing SSC preload and aiding concentric force production (10, 19). As braking impulse is equal to unweighting impulse (29), it could be suggested that unweighting-phase variables such as minimum eccentric force (normalised to body mass; F_{min}) should be monitored as a jump strategy variable. There are conflicting results on the relationship between F_{min} and jump performance, with two studies (8, 17) finding no significant differences between groups separated by jump height performance, while another (33) found that athletes who jumped higher had a greater unweighting. An investigation exploring the longitudinal changes in jump strategy observed significant changes in F_{min} after 10 weeks of training, with greater unweighting occurring concomitantly with improvements in jump height, although no direct relationship between these variables was investigated (4). The research surrounding F_{min} as a component of jump strategy is limited and its influence on CMJ performance is unclear.

The direct relationships between eccentric biomechanical parameters and CMJ performance are not fully understood, and an investigation into these variables could offer deeper insight into the effects of various jump strategies on performance. Therefore, the aim of this study was to determine the relationships between eccentric-phase parameters and markers of jump performance. It was hypothesised that lower minimum eccentric force (F_{min}), downwards velocity (V_{ecc}), countermovement depth (D_{ecc}) and braking impulse ($I_{braking}$) and greater SSC preload (F_{0V}) are associated with increased jump height, RSI_{mod} and TO_p.

4.2 Materials and methods

4.2.2 Participants

A total of 201 female (n = 82; mean ± SD height: 1.71 ± 0.09 m; mass: 65.5 ± 9.1 kg; age: 21.8 ± 3.35 yr) and male athletes (n = 119; mean ± SD height: 1.80 ± 0.08 m; mass: 83.8 ± 16.2 kg; age: 21.6 ± 2.9 yr) volunteered and provided written informed consent to participate in this study. Participants were from a variety of different sport codes, including netball (female, n = 35), rugby (male, n = 68), hockey (female, n = 28; male, n = 25), swimming (female, n = 12; male, n = 7), and track athletes (female, n = 8; male, n = 19). None of the participants reported any injuries at the time of testing and all competed at collegiate level. All participants were over the age of 18 and did not require parental consent to participate in this study. Ethical approval was granted by Faculty of Health Sciences Research Ethics Committee (771/2020).

4.2.3 Procedures

Each participant was required to attend a single testing occasion. Every participant completed a standardised warm up, including three sub-maximal CMJs with increasing intensity for each jump. All participants were familiar with the CMJ testing protocol and previously performed CMJs as part of the routine athlete-monitoring programme. Participants were asked to stand on the dual force platform (JM6090-06, Bertec, USA) with one foot on each plate. Participants stood still prior to initiating the first CMJ to allow determination of bodyweight (BW) for post-testing analysis and then performed three countermovement jumps (with between 30 and 60 seconds of rest between each jump) with their arms akimbo to eliminate the use of arm swing. Participants were instructed to “jump as high as possible, as fast as possible” and to “maintain full extension during the flight phase until the moment of touchdown”. Participants used a self-selected countermovement depth. A CMJ trial was repeated if the participant removed their hand/s from their hips when performing a CMJ, did not land on the platform with both feet, tucked their legs during the flight phase, or if their legs were not fully extended on touch down.

4.2.4 Data collection and processing

Ground reaction force data were sampled at 1000 Hz and recorded using ForceDecks software (VALD Performance, Australia). The variables of interest were calculated from the force-time trace. Jump height was calculated using COM take-off velocity, which was determined through the impulse-momentum method (21). Take-off velocity was scaled to body mass and presented as TO_p (23).

CMJ phases were defined as described previously (26). The first CMJ phase was the weighing phase, where the participant was asked to stand completely still on the force platforms for at least one second to record BW and eliminate signal noise prior to initiating the CMJ (26). The eccentric phase was divided into two distinct phases – the unweighting and braking phases. The initiation of the unweighting phase was identified when the vertical force decreased by a threshold of 20 N less than BW (26). The braking phase began from the moment after peak negative velocity to the moment negative COM velocity equalled zero (which coincided with the lowest depth of the countermovement). The propulsion phase began when the participant's upwards COM vertical velocity increased above a threshold of 0.01 $m.s^{-1}$ and ended when the participant was no longer in contact with the force platform (< 30 N GRF threshold) and had entered the flight phase of the CMJ (26). Displacement (D_{ecc}) and velocity (V_{ecc}) in the downwards direction and minimum eccentric force (F_{min}) in the downwards direction were considered negative. All force metrics (including F_{min}, F_{0V} and $I_{braking}$) were reported as net force values (GRF – BW) and normalised to body mass. The metric $I_{braking}$ was calculated as the area under the force-time graph between V_{ecc} and initiation of the concentric phase. Time to take-off (TTT) was included in the descriptive statistics as it is a component required for the calculation of RSI_{mod}.

4.2.5 Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics (Version 27) for Windows. The two best CMJs were selected based on jump height, and an averaged value for each variable was used for statistical analysis. The interquartile rule was used to identify and remove outliers. Observations were considered outliers if they were lower than the first quartile minus 1.5 times the interquartile range, or higher than the third quartile plus 1.5 times the interquartile range. Data were presented as means and standard deviations to represent centrality and spread of data. Normality was assessed using the Kolmogrov-Smirnov test with an alpha level set at 0.05, where a p value greater than 0.05 indicated that the data were normally distributed. The coefficient of variation (CV) was included to provide context regarding the absolute consistency of each variable and was calculated by dividing the standard deviation by the mean score between trials and expressed as a percentage (5). A CV of less than 10% was considered to be reflective of acceptable variability (5).

A Pearson correlation coefficient was used to determine the relationships between biomechanical eccentric-phase parameters (movement strategy) of the CMJ (F_{min},

V_{ecc}, D_{ecc}, $I_{braking}$ and F_{0V}) and jump performance measures (jump height, TO_p and RSI_{mod}). The magnitude of the r values was interpreted as follows: trivial (r = 0.00 – 0.09); small (r = 0.10 – 0.29); moderate (r = 0.30 – 0.49); large (r = 0.50 – 0.69); very large (r = 0.70 – 0.89); and extremely large (r = 0.90 – 1.00) (14). The variables D_{ecc}, V_{ecc} and F_{min} were presented and analysed as negative values and the correlation results interpreted accordingly. A stepwise linear regression was used to identify possible predictors of jump performance using the biomechanical parameters of interest as the candidate variables (6). The statistical significance threshold was set a priori at $\alpha = 0.05$ for both the Pearson correlation coefficient and the stepwise linear regression. Multicollinearity was assessed before conducting the stepwise regression and indicated a collinearity between V_{ecc} and $I_{braking}$ (variance inflation factor = 2.63-2.99) that exceeded the acceptable threshold (16); hence $I_{braking}$ was excluded, as it did not provide statistically significant contributions to the regression model.

4.3 Results

The means and standard deviations of all variables of interest for female and male participants are shown in Table 4.1. The CVs ranged from 1.6% to 16.7%, with the highest within-subject variability observed for F_{min}.

Table 4.1 CMJ descriptive statistics by sex

	Females (n = 82)				**Males (n = 119)**			
	Mean		SD	CV	Mean		SD	CV
Jump height (cm)	27.5	±	5.7	4.2	41.3	±	6.7	3.1
RSI_{mod} (AU)	0.36	±	0.09	8.4	0.55	±	0.12	6.3
TO_p ($kg.m.s^{-1}$)	151	±	3	2.1	237	±	4	1.6
D_{ecc} (cm)	-29.1	±	4.8	9.2	-33.7	±	6.2	7.2
V_{ecc} ($m.s^{-1}$)	-1.06	±	0.21	10.6	-1.25	±	0.27	8.3
TTT (ms)	817	±	116	7.4	794	±	145	5.5
$I_{braking}$ ($N.s.kg^{-1}$)	1.04	±	0.27	9.5	1.25	±	0.31	9.2
F_{min} ($N.kg^{-1}$)	-5.41	±	0.83	16.7	-6.66	±	0.67	11.8
F_{0V} ($N.kg^{-1}$)	11.8	±	1.3	11.4	14.8	±	1.1	8.3

AU = arbitrary units, RSI_{mod} = modified reactive strength index, TO_p = take-off momentum, D_{ecc} = countermovement displacement, V_{ecc} = eccentric peak velocity, TTT = time to take-off, $I_{braking}$ = braking impulse, F_{min} = minimum eccentric force and F_{0V} = force at zero velocity.

Correlations between jump strategy metrics and markers of jump performance ranged from trivial (r = -0.03) to very large (r = 0.72 and 0.70 respectively) for females and males (Table 4.2). In both females and males, D_{ecc} was the best correlate of jump height (-0.27 and -0.37 respectively), with larger amplitude countermovements resulting in better jump heights. F_{0V} was the best correlate for RSI_{mod} in both females (r = 0.72) and males (r = 0.70), indicating that a greater F_{0V} was related to greater RSI_{mod}. The best correlate of TO_p in females and males was F_{min} (r = -0.37 and -0.62 respectively), where a smaller F_{min} (greater unweighting) was related to greater TO_p.

Table 4.2 CMJ correlations between jump strategy metrics and markers of jump performance

	Females (n = 82)			Males (n = 119)		
	Jump height	RSI_{mod}	TO_p	Jump height	RSI_{mod}	TO_p
F_{min}	0.14	-0.34*	-0.37*	0.07	-0.53*	-0.62*
V_{ecc}	-0.14	-0.49*	-0.15	-0.21*	-0.60*	-0.27*
D_{ecc}	-0.27*	0.07	-0.03	-0.37*	0.12	-0.03
$I_{braking}$	0.08	0.46*	0.11	0.10	0.50*	0.18
F_{0V}	0.19	0.72*	0.16	0.14	0.70*	0.27*
TTT	0.06	-0.58*	-0.10	0.12	-0.66*	-0.19*

* $p < 0.05$

In terms of the stepwise regression prediction of jump height (Table 4.3), it was found that the best predictor model for males and females involved the same three variables (D_{ecc}, F_{0V}, and F_{min}), explaining ~22% of the variance associated with jump height. The only predictor of RSI_{mod} for female athletes was F_{0V}, explaining 51.2% of the variance ($p < 0.05$), whereas a three-predictor model (F_{0V}, V_{ecc}, D_{ecc}) best explained the variance in RSI_{mod} in males (53.2%). For TO_p, a four-predictor model (F_{min}, V_{ecc}, D_{ecc}, F_{0V}) best explained the variance in females (27.3%) and males (64.9%).

Table 4.3 Stepwise regression model summary jump strategy metrics and markers of CMJ performance

		Females (n = 82)				**Males (n = 119)**		
Model		r	R^2	Adjusted R^2		r	R^2	Adjusted R^2
Jump height								
Single predictor	D_{ecc}	0.269	0.072	0.061	D_{ecc}	0.372	0.139	0.131
Two predictors	D_{ecc}, F_{0V}	0.383	0.147	0.126	D_{ecc}, F_{0V}	0.438	0.192	0.178
Three predictors	D_{ecc}, F_{0V}, F_{min}	0.514	0.265	0.237	D_{ecc}, F_{0V}, F_{min}	0.484	0.234	0.214
RSI_{mod}								
Single predictor	F_{0V}	0.719	0.517	0.512	F_{0V}	0.682	0.465	0.460
Two predictors					F_{0V}, V_{ecc}	0.717	0.513	0.505
Three predictors					F_{0V}, V_{ecc}, D_{ecc}	0.729	0.532	0.532
TO_p								
Single predictor	F_{min}	0.374	0.140	0.129	F_{min}	0.624	0.389	0.384
Two predictors	F_{min}, V_{ecc}	0.438	0.192	0.172	F_{min}, V_{ecc}	0.688	0.473	0.464
Three predictors	F_{min}, V_{ecc}, D_{ecc}	0.490	0.240	0.211	F_{min}, V_{ecc}, D_{ecc}	0.767	0.589	0.578
Four predictors	F_{min}, V_{ecc}, D_{ecc}, F_{0V}	0.556	0.309	0.273	F_{min}, V_{ecc}, D_{ecc}, F_{0V}	0.813	0.661	0.649

4.4 Discussion

The eccentric phase of the CMJ is thought to be an important determinant of CMJ performance, as it has been suggested to influence SSC utilisation. The aim of this study was to determine the relationships between eccentric biomechanical parameters and markers of jump performance. The main findings of this study were: 1) all markers of jump performance were found to have at least one moderate to large correlation with a jump strategy variable, with the exception of jump height for females; 2) the best predictor variables for jump height were D_{ecc}, F_{0V} and F_{min} for both females and males; 3) the best predictor variables for TO_p were F_{min}, V_{ecc}, D_{ecc} and F_{0V} for both females and males; and 4) F_{0V} was the best predictor for RSI_{mod} in female participants while the combination of F_{0V}, V_{ecc} and D_{ecc} was the best predictor for RSI_{mod} in male participants.

Eccentric-phase variables, in particular movement amplitude (D_{ecc}) and velocity (V_{ecc}), have been thought important determinants for maximising jump height (1, 4, 31). In this study, D_{ecc} had the largest univariate relationship with jump height; however, this only exceeded the moderate threshold in the male athletes (r = -0.37). The results of this study align with the findings of previous authors, who have observed that greater jump heights are associated with increased D_{ecc} (8, 12, 17, 18, 30, 31). The relationship between D_{ecc} and jump height observed in this study could be explained by the influence amplitude has on storage of elastic energy, where a greater stretch would enhance the benefits of the SSC mechanism (2). As for the regression model results, ~22% of the variance in jump height was predicted by the combination of greater unweighting (F_{min}), countermovement displacement (D_{ecc}) and SSC preload (F_{0V}). Although these results may seem inconsequential, the fact that almost a quarter of the variance in jump height can be explained by variables occurring during the eccentric phase places a relative importance on the jump strategy used during this phase (4, 10, 33). To the author's knowledge, only one other study has used a stepwise regression to identify predictor variables for CMJ height. Merrigan et al. (28) observed similar results to this study, with D_{ecc} (~5%) and eccentric braking peak force (~6%) (measured within a comparable temporal proximity to F_{0V}) to be valued predictors of the variance in jump height in collegiate male American football players (n = 82). The results of this study add to the growing interest in the relationships between jump strategy and jump performance, highlighting the potential and influence that eccentric-phase parameters have on jump height.

The only jump strategy variable that was observed to have moderate to large correlations with TO_p for both females (r = -0.37) and males (r = -0.62) was F_{min}. Similar results were reported by Harry et al. (12), suggesting that greater unloading of bodyweight during the unweighting phase is associated with increased TO_p. However, in contrast to the trivial correlations between D_{ecc} and TO_p found in this study, Harry et al. (12) observed large correlations (r = -0.55) between D_{ecc} and TO_p in recreationally active females (n = 31). The conflicting results between this investigation and that of Harry et al. (12) may be due to the differences in level of athleticism between female populations. Similar body mass (~3%) and D_{ecc} (~3%) were reported, while the differences in jump height (~20%) suggest that females in this study achieved greater take-off velocities (12). The best predictor variables of TO_p were F_{min}, V_{ecc}, D_{ecc} and F_{0V} for both females and males. The predictive potential of these variables highlights the influence the pre-stretch has on TO_p, whereby larger amplitudes (D_{ecc}) and greater velocities (V_{ecc} and F_{min}) result in increased stored elastic potential energy (SSC preload) that can be reutilised towards concentric force production. Jump height and TO_p shared a similar set of predictor variables (with the exclusion of V_{ecc}), which is likely due to their common relationship with take-off velocity. The combined results from the correlation analyses and stepwise regression results of this study suggest that greater unloading of bodyweight (F_{min}), or pre-stretch acceleration, should be the main priority when seeking to improve TO_p.

The strongest univariate correlations were found between F_{0V} and RSI_{mod} (females: r = 0.72, males r = 0.70). Jump strategy metrics have previously been observed to be related to RSI_{mod}, with moderate to large correlations suggesting that greater eccentric velocity, shorter TTT, and greater F_{0V} and $I_{braking}$ were related to better performance, while trivial correlations were observed with D_{ecc} (1, 10, 12, 20, 22). These shared observations may suggest that the velocity of the pre-stretch (V_{ecc}), rapid deceleration (F_{0V} and $I_{braking}$) and phase-specific quickness (TTT) should be focused on if a greater RSI_{mod} is desired, rather than prioritising eccentric amplitude (D_{ecc}), which is perhaps not surprising given that time is the denominator of the ratio. As previously mentioned, the metric F_{0V} may be indicative of SSC preload and is the quantitative difference between a vertical jump that utilises the SSC mechanism and that which does not (i.e. CMJ vs squat jump) (2, 19). The performance measure RSI_{mod} has previously been purported to be an indirect measure of SSC utilisation, and its relationship to F_{0V} observed in this study and previous investigations may help to support this claim (1, 12, 22, 34). The results from the stepwise regression indicated that F_{0V} could predict 47% and 52% of the variance in RSI_{mod} in males and females respectively. The combined results of the correlation analysis and stepwise regression indicate that F_{0V} is a key jump strategy metric and should be monitored for changes when seeking to improve RSI_{mod}.

There are potential limitations when applying a stepwise regression analysis in this study. The risk for a type-1 error increases with every additional predictor variable added to the model; however, this risk should have been offset by the large sample size used in this study. The CVs observed for F_{min} and V_{ecc} in this study indicated that these metrics do not reflect acceptable variability; however, previous authors have reported contrasting variability results to those of this study (12, 13, 25). Practitioners must use caution when analysing or reporting these variables without confirming the variability of the data.

4.5 Conclusion

Although jump performance is a direct result of the net impulse occurring in the concentric phase, the results from the correlation analysis and stepwise regression highlight the influence that jump strategy prior to concentric initiation has on the outcome of a CMJ. The combined findings of the correlation analysis and stepwise regression revealed that eccentric-phase parameters, particularly D_{ecc}, V_{ecc}, F_{0V} and F_{min}, are important jump strategy metrics for maximising jump height, TO_p and RSI_{mod}. The largest univariate relationship and single predictor for jump height was D_{ecc}, while the same was observed between F_{min} and TO_p, and F_{0V} and RSI_{mod}. These results suggest that the influence of eccentric unweighting, movement amplitude and achieving high GRF at the end of the eccentric phase is significant for vertical jump performance. Coaches and athletes should consider these findings when monitoring CMJ performance and designing training programmes.

4.6 Chapter summary

This chapter addressed objective 3: to investigate the relationship between eccentric-phase parameters and measures of jump performance, specifically jump height, TO_p and RSI_{mod}, involving 201 collegiate athletes from various sports. The findings of Chapter 4 underscore the importance of monitoring eccentric variables of interest when assessing jump strategy and performance. Transitioning to the next chapter, it becomes essential to consider the influence of lower-body strength on both CMJ performance and jump strategy. Musculoskeletal strength, particularly in the lower-body, is fundamental to the ability to generate and control force during dynamic tasks such as jumping, directly impacting the effectiveness of eccentric-phase jump strategy variables. However, limited information exists in literature concerning the interactions and associations between maximal strength, jump strategy and jump performance. Therefore, the following chapter examines the influence of lower-body strength on CMJ performance and adoption of different jump strategies.

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Chapter 5: The influence of maximal isometric strength and timing of peak ground reaction force on countermovement jump performance and strategy

Abstract

This study investigated the influence of maximal strength and timing of peak force (T_{PF}) on countermovement jump (CMJ) performance and kinematic and kinetic parameters that characterise jump strategy. Ground reaction force data during the CMJ and isometric squat (ISQ) were collected from 165 collegiate athletes. Participants were grouped into early and late T_{PF} groups based on the timing of peak force during the CMJ, and strong and weak groups, based on relative ISQ peak force. Both male and female early T_{PF} groups were found to have greater unweighting (F_{min}) (ES= -1.0 and -1.60), eccentric peak velocity (V_{ecc}) (ES= -1.32 and -1.97) and force at zero velocity (F_{0V}) (ES= 1.66 and 1.76) than the late T_{PF} groups. When separated by relative strength, the strong groups jumped higher than the weak groups (ES= 0.64 and 0.58). Strong males had greater modified reactive strength index (ES= 0.68), V_{ecc} (ES= 0.66), countermovement depth (ES= 0.42), F_{0V} (ES= 68), and F_{min} (ES= 0.49), as well as earlier T_{PF} (ES= 0.45) than weak males did, while no significant differences were observed for jump strategy between female groups. These findings highlight the importance of enhancing maximal strength for improved jump performance, suggesting a potential minimum threshold for effective use of the stretch-shorten cycle in optimising the CMJ.

5.1 Introduction

Maximal strength is a key determinant of improved sports performance because the ability of a muscle or group of muscles to exert force against resistance is an important factor for generating power and speed and changing the momentum of the body's centre of mass (COM) (1, 2). This is particularly important in sports that require 'explosive' movements, such as jumping, sprinting and throwing (3). Recently, maximal lower-body strength has been monitored and assessed through isometric tests such as the isometric squat (ISQ) or isometric mid-thigh pull (4). These isometric tests are not limited by technical proficiency and can be expressed as a maximal voluntary isometric contraction, which typically is greater than a concentric dynamic one repetition maximum according to the force-velocity relationship of muscle (2, 4). Practitioners typically use the results from the isometric tests in conjunction with those from dynamic tasks such as the countermovement jump (CMJ) to monitor athletes and guide training prescriptions. Positive associations between maximal-strength tests (dynamic and isometric) and the CMJ assessment have been previously reported, thus providing practitioners with a rationale for increasing maximal strength to improve jump performance (5, 6). However, possessing high maximal strength alone does not fully determine jump performance, as this is also influenced by the movement strategy that the athlete uses to execute the jump (7, 8).

The vertical amplitude and velocity of an athlete's COM is reflected in the vertical GRF generated throughout the CMJ. The manner in which the COM moves through the different phases of the CMJ is referred to as jump strategy (9, 10), and has been suggested to provide valuable information regarding an athlete's utilisation of the stretch-shorten cycle (SSC) (7). The eccentric and concentric phases of the CMJ describe the downwards and upwards motions (respectively) of the COM. The eccentric phase has been divided into unweighting and braking phases, as the impulses generated within each phase are equal to each other (11). A further subdivision of the unweighting phase into unloading (before minimum GRF) and yielding (after minimum GRF) has been suggested to allow researchers to gain a more thorough understanding of an athlete's neuromuscular function (12). Exercises that couple eccentric and concentric muscle actions utilise the SSC and have been observed to increase GRF at concentric initiation (SSC preload) more than concentric-only exercises (e.g. squat jump), in addition to producing better jump performance (13). The underlying theories for the performance-enhancement effects of the SSC are attributed to one or a combination of the following: 1) storage and release of elastic potential energy in tendons and muscles and 2) potentiation of the contractile machinery pertaining to rate coding, motor unit recruitment and synchronisation (13). The GRF at concentric initiation during the CMJ, or force at zero velocity (F_{0V}), influences the performance-enhancing effects of the SSC, and a jump strategy characterised by greater unloading of bodyweight, eccentric peak velocity and downwards displacement would increase F_{0V} and potentiate the SSC (7, 14). However, previous researchers have suggested that an athlete's jump strategy and ability to generate large F_{0V} is associated with greater maximal strength (14-16). An athlete adopting a jump strategy to increase F_{0V} may not have the necessary strength to effectively decelerate their COM and transfer the benefits of the SSC towards concentric performance.

Although eccentric-phase jump strategy may influence overall CMJ performance, the execution of the concentric phase ultimately determines jump height (17). Previous authors have identified two main variations in CMJ strategy during the concentric phase by analysing the force-time series and have categorised them as unimodal (single vertical force peak) and bimodal (two distinct vertical force peaks) (7, 18). While there is some debate as to which modality represents superior jump performance (19, 20), researchers have recently suggested that the modality of the curve may be less important than the timing of peak force (18). An earlier peak force, occurring at the moment of transition between eccentric and concentric muscle actions (amortisation) or early in the concentric phase, has been associated with enhanced CMJ performance – for example jump height, modified reactive strength index (RSI_{mod}) and take-off momentum (TO_p) – and may reflect an efficient use of the SSC (7, 18, 20). The ability to produce peak force at amortisation or early in the concentric phase may be dependent on not only the eccentric-phase jump strategy, but also on the maximal strength capacity of an athlete. Although it is well understood that maximal strength is associated with concentric performance in jumping, the interaction between maximal strength, jump strategy and timing of peak force is not fully established. It would be of benefit for practitioners to understand the influence of strength on the timing of peak force production, as it could enable them to prescribe better training strategies to improve utilisation of the SSC and jump performance.

The optimal jump strategy has been described as a rapid unweighting during the eccentric phase to maximise F_{0V} and generate peak force early in the concentric phase (7). However, this jump strategy may be dependent on maximal strength to tolerate the increased deceleration demands and effectively transfer the benefits of the SSC towards concentric performance. Therefore, the aim of this investigation was to determine the influence of maximal isometric strength and timing of peak force on jump strategy and CMJ performance. It was hypothesised that better CMJ performance and a jump strategy that adopted greater unweighting, higher eccentric peak velocity and countermovement depth would be associated with (i) earlier peak force occurrence during the concentric phase and (ii) greater isometric strength.

5.2 Materials and methods

5.2.1 Participants

A total of 165 female (n = 61; mean ± SD height: 1.71 ± 0.09 m; mass: 65.1 ± 7.8 kg; age: 22.0 ± 3.7 yr) and male athletes (n = 104; mean ± SD height: 1.80 ± 0.08 m; mass: 84.7 ± 16.5 kg; age: 21.6 ± 3.0 yr) volunteered and provided informed consent to participate in this study. Participants were competitive athletes from a variety of different sport codes, including netball (female n = 25), rugby (male n = 60), hockey (female n = 22, male n = 22), swimming (female n = 7, male n = 6), and short-distance track athletics (female n = 7, male n = 16). None of the participants reported any injuries at the time of testing and all competed at a collegiate level of competition with at least six months of supervised resistance training. All participants were over the age of 18 and did not require parental consent to participate in this study. Ethical approval was granted by Faculty of Health Sciences Research Ethics Committee (771/2020).

5.2.2 Procedures

5.2.2.1 CMJ

Each participant was required to attend a single testing occasion. Every participant completed a standardised warm up, including three sub-maximal CMJs with increasing intensity for each jump. All participants were familiar with the CMJ testing protocol and had previously performed CMJs as part of routine athlete-monitoring programme. Participants were asked to stand on the dual force platform (JM6090-06, Bertec, USA) with one foot on each plate. Participants stood still prior to initiating the first CMJ to allow determination of body weight (BW) for post-testing analysis. They then performed three countermovement jumps (with between 30 and 60 seconds of rest between each jump) with their arms akimbo to eliminate the use of arm swing. Participants were instructed to “jump as high as possible, as fast as possible” and to “maintain full extension during the flight phase until the moment of touchdown”. Participants used a self-selected countermovement depth. A CMJ trial was repeated if the participant removed their hand/s from their hips when performing a CMJ and/or did not land on the platform with both feet fully extended on touch down. After the participant completed the three CMJ trials, a five-minute rest period was allocated before initiating the ISQ testing.

5.2.2.2 ISQ

The ISQ trials were completed on the same dual force plates, surrounded by a custom-built squat rack fitted on either side of the plates. An immovable bar was placed inside the rack at the height required to achieve a knee and hip angle of 60^0 (measured with a goniometer) for each individual participant. The participants were instructed to place a foot on each platform directly under the bar and approximately shoulder width apart and stood still (while not touching the bar) prior to initiating the first ISQ to allow determination of BW for post-testing analysis. Participants were instructed to push upwards against the bar with maximal effort with their hands resting on the bar without pushing. Each participant was required to complete three trials with maximal effort. Each trial lasted for three seconds, with rests of between 30 seconds and 60 seconds between trials. A trial was repeated if the participant did not maintain contact with the bar throughout the trial and/or sustain maximal effort for the full three seconds.

5.2.3 Data collection and processing

Ground reaction force data were sampled at 1000 Hz and recorded using ForceDecks software (VALD Performance, Australia). The variables of interest were calculated from the force-time data. Jump height was calculated using COM take-off velocity, which was determined through the impulse-momentum method (21). The weighing, unweighting, braking and propulsion phases of the CMJ were defined as described previously (22). During the weighing phase participants were instructed to stand still on the force platforms until signal noise was eliminated, whereafter BW was recorded. The unweighting and braking phases are subphases of the eccentric phase, describing downwards acceleration and deceleration respectively. The initiation of the unweighting phase was identified when vertical GRF decreased by 20 N less than BW (22). The braking phase was defined as the moment after eccentric peak velocity until the moment eccentric COM velocity equalled zero (coinciding with eccentric peak COM displacement) (22). The propulsion phase began when the participant's concentric COM vertical velocity increased above a threshold of 0.01 $m.s^{-1}$ and ended when the participant was no longer in contact with the force platform (< 30 N GRF threshold) and had entered the flight phase of the CMJ (22).

Downwards displacement (D_{ecc}), velocity (V_{ecc}) and minimum force (F_{min}) during the eccentric phase were considered negative. All force metrics – including ISQ peak force (ISQ_{PF}), F_{min}, F_{0V} and concentric peak force (F_{con}) – were reported as net force values (GRF – BW) and normalised to body mass. Time to take-off (TTT) was included in the descriptive statistics as it is a component required for the performance measure RSI_{mod}, which is calculated by dividing jump height by TTT (23). The product of take-off velocity and body mass was used to calculate TO_p while T_{PF} was calculated as the time from F_{0V} to peak vertical GRF and expressed as a percentage of the concentric-phase duration.

5.2.4 Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics (Version 27) for Windows. The interquartile rule was used to identify outliers, whereby cases lower than the first quartile minus 1.5 times the interquartile range or those above the third quartile plus 1.5 times the interquartile range were considered outliers. If an outlier was considered to be a reflection of a trial that was performed incorrectly, all other variables within that trial were omitted so that normal performance variation was not excluded. Data were presented as means and standard deviations to represent centrality and spread of data. Normality was assessed using the Kolmogorov-Smirnov test, with an alpha level set at 0.05, where a p value greater than 0.05 indicated that the data were normally distributed. Of the three trials performed by each participant for the CMJ and ISQ, two trials were selected (based on the two highest jump height and two largest ISQ_{PF} scores) and averaged for each participant to increase within-subject reliability.

Subgroups were created by dividing the sample at the mean for: (i) time to peak force (T_{PF}) and categorised as “early” and “late” groups; and, (ii) maximal strength (ISQ_{PF}) to create “strong” and “weak” groups. The T_{PF} classification used the combined data from both females and males, with a mean of 21.8%. In absolute terms, the mean T_{PF} for the early group was 8 ms into the concentric phase and 166 ms for the late group. Participants that were inconsistently classified in the two T_{PF} groups across their two trials were omitted from the dataset (n = 37). For strength classification, females and males were analysed separately, with the group classification thresholds identified at 23.0 $N.kg^{-1}$ for females and 32.7 $N.kg^{-1}$ for males.

An independent t-test was used to determine the differences between early and late T_{PF} on CMJ performance variables (jump height, RSI_{mod} and TO_p), ISQ_{PF} and jump strategy (F_{min}, V_{ecc}, D_{ecc} and F_{0V}). A second independent t-test was used to determine the differences between strong and weak groups in CMJ performance and jump strategy (including T_{PF}). The effect size (Cohen’s d) was used to determine the magnitude of the differences between groups, and values were selected based on the standards used by previous investigators (20, 24) and interpreted as trivial (≤0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (2.0–4.0)

(25). Statistical significance was set a priori $\alpha = 0.05$ for the independent t-test and, due to the unequal sample sizes between groups, a Welch's t-test was conducted.

5.3 Results

Means and standard deviations were presented for variables of interest for males and females in Table 5.1 to provide descriptive statistical context for the entire sample. Tables 5.2 and 5.3 include mean, standard deviations and Cohen's d for female and male groups, separated by T_{PF} and ISQ_{PF} respectively.

Table 5.1 Descriptive statistics for the CMJ and ISQ for females and males

	Females			Males		
	Mean		**SD**	**Mean**		**SD**
Performance variables						
ISQ_{PF} (N.kg^{-1})	22.9	±	5.4	32.7	±	6.4
Jump height (cm)	28.4	±	6.2	41.7	±	7.0
RSI_{mod} (AU)	0.37	±	0.10	0.56	±	0.13
TO_p (kg.m.s^{-1})	152	±	20	239	±	47
Jump strategy variables						
F_{min} (N.kg^{-1})	-5.5	±	2.0	-6.6	±	2.1
V_{ecc} (m.s^{-1})	-1.07	±	0.26	-1.28	±	0.29
D_{ecc} (cm)	-29.1	±	5.6	-33.9	±	6.6
F_{0V} (N.kg^{-1})	12.1	±	3.1	14.9	±	3.5
T_{PF} (%)	23.0	±	31.5	20.9	±	28.2
Additional kinetic and kinematic variables						
TTT (ms)	822	±	149	791	±	154
F_{con} (N.kg^{-1})	13.3	±	2.6	16.2	±	2.5

ISQ_{PF} = maximum isometric force; RSI_{mod} = modified reactive strength index; TO_p = take-off momentum; F_{min} = minimum eccentric force; V_{ecc} = eccentric peak velocity; D_{ecc} = downwards displacement; F_{0V} = force at zero velocity; T_{PF} = timing of peak force; TTT = time to take-off; F_{con} = concentric peak force; AU = arbitrary units; SD = standard deviation.

The mean T_{PF} in the early groups was 2.4 ± 6% and 3.7 ± 7.6% into the concentric phase for females and males, respectively, whereas the late T_{PF} groups were 65.3 ± 15.9% and 59.7 ± 16.7%. For all the performance variable comparisons, small and non-significant differences between T_{PF} groups were noted.

For the jump strategy variables, however, all but D_{ecc} were found to differ significantly between early and late T_{PF} groups across both sexes. The early T_{PF} group was found to have lower F_{min} (M: ~27%, ES = -1.0; F: ~40%, ES = -1.60) and greater V_{ecc} (M: ~24%, ES = -1.32; F: ~32%, ES = -1.97) and F_{0V} (M: ~4.4%, ES 1.66; F: ~32%, ES = 1.76). Early T_{PF} males were found to have significantly greater F_{con} (~11%, ES = 0.63) and shorter TTT (~14%, ES = -0.82) than those of late males, while early females had a significantly shorter TTT than late females did (~19%, ES = -1.39).

ISQ_{PF} means for the strong groups were 27.4 ± 3.7 $N.kg^{-1}$ and 38.2 ± 4.3 $N.kg^{-1}$, whereas those for the weak groups were 18.9 ± 2.9 $N.kg^{-1}$ and 27.9 ± 3.6 $N.kg^{-1}$ for females and males respectively. Statistically significant differences in jump height were observed between strong and weak groups, where strong females (~13%; ES = 0.64) and strong males (~9%; ES = 0.58) jumped higher than participants in the weak groups did. Strong males had statistically greater RSI_{mod} (~13%; ES = 0.68) than weak males, while no significant differences were observed for RSI_{mod} between strong and weak females. No significant differences were noted for TO_p in either sex.

All jump strategy variables between male groups were significantly different, where strong males demonstrated lower F_{min} (~14%; ES = 0.49), greater V_{ecc} (~13%; ES = 0.66), D_{ecc} (~8%; ES = 0.42) and F_{0V} (~14%; ES = 0.68), and earlier T_{PF} (~46%; ES = 0.45) than weak males did. No significant differences in jump strategy were observed when comparing strong and weak female groups. Strong males also had significantly greater F_{con} than weak males (10%, ES = 0.77), while no other significant differences were observed.

Table 5.2 CMJ and ISQ variables separated by T_{PF} for female and male athletes

	Females								Males							
	Early (n = 41)			Late (n = 20)					Early (n = 72)			Late (n = 32)				
	Mean		**SD**	**Mean**		**SD**	**d**	***p***	**Mean**		**SD**	**Mean**		**SD**	**d**	***p***
Performance variables																
ISQ_{PF} (N.kg^{-1})	22.4	±	5.2	24.1	±	5.8	-0.32	0.242	33.2	±	6.5	31.5	±	6.4	0.27	0.210
Jump height (cm)	27.5	±	5.2	30.4	±	7.7	-0.48	0.087	40.8	±	7.2	43.5	±	6.1	-0.40	0.066
RSI_{mod} (AU)	0.39	±	0.09	0.35	±	0.11	0.39	0.160	0.57	±	0.13	0.52	±	0.12	0.37	0.085
TO_p (kg.m.s^{-1})	154	±	18	149	±	23	0.26	0.351	244	±	46	235	±	49	0.21	0.335
Jump strategy variables																
F_{min} (N.kg^{-1})	-6.29	±	1.72	-3.79	±	1.15	-1.60*	<.001	-7.18	±	1.81	-5.28	±	2.09	-1.00*	<.001
V_{ecc} (m.s^{-1})	-1.19	±	0.20	-0.82	±	0.16	-1.97*	<.001	-1.38	±	0.25	-1.06	±	0.25	-1.32*	<.001
D_{ecc} (cm)	-29.3	±	5.3	-28.8	±	6.2	-0.09	0.733	-34.3	±	6.5	-32.8	±	6.6	-0.23	0.290
F_{0V} (N.kg^{-1})	13.5	±	2.3	9.2	±	2.6	1.76*	<.001	16.3	±	2.5	11.7	±	3.3	1.66*	<.001
Additional kinetic and kinematic variables																
F_{con} (N.kg^{-1})	13.7	±	2.4	12.5	±	2.8	0.50	0.072	16.7	±	2.5	15.2	±	2.3	0.63*	0.004
TTT (ms)	765	±	99	940	±	168	-1.39*	<.001	752	±	124	871	±	182	-0.82*	<.001

ISQ_{PF} = maximum isometric force; RSI_{mod} = modified reactive strength index; TO_p = take-off momentum; F_{min} = minimum eccentric force; V_{ecc} = eccentric peak velocity; D_{ecc} = downwards displacement; F_{0V} = force at zero velocity; T_{PF} = timing of peak force; TTT = time to take-off; F_{con} = concentric peak force; AU = arbitrary units; SD = standard deviation; * = $p < 0.05$.

Table 5.3 CMJ and ISQ variables separated by relative maximal isometric strength for female and male athletes

	Females								Males							
	Strong (n = 29)			Weak (n = 32)					Strong (n = 48)			Weak (n = 56)				
	Mean		**SD**	**Mean**		**SD**	**d**	***p***	**Mean**		**SD**	**Mean**		**SD**	**d**	***p***
Performance variables																
Jump height (cm)	30.4	±	6.5	26.6	±	5.4	0.64*	0.016	43.7	±	6.6	39.8	±	6.9	0.58*	0.004
RSI_{mod} (AU)	0.39	±	0.08	0.36	±	0.11	0.35	0.183	0.60	±	0.13	0.52	±	0.11	0.68*	<.001
TO_p (kg.m.s^{-1})	157	±	16	148	±	22	0.43	0.101	244	±	47	239	±	47	0.11	0.564
Jump strategy variables																
F_{min} (N.kg^{-1})	-5.29	±	1.76	-5.63	±	2.12	0.17	0.513	-7.13	±	1.86	-6.14	±	2.17	-0.49*	0.015
V_{ecc} (m.s^{-1})	-1.07	±	0.22	-1.08	±	0.29	0.03	0.898	-1.38	±	0.26	-1.20	±	0.28	-0.66*	0.001
D_{ecc} (cm)	-30.0	±	5.0	-28.4	±	6.1	-0.29	0.266	-35.3	±	6.6	-32.6	±	6.3	-0.42*	0.037
F_{0V} (N.kg^{-1})	12.1	±	2.6	12.1	±	3.6	-0.02	0.936	16.1	±	3.5	13.9	±	3.2	0.68*	<.001
T_{PF} (%)	24.0	±	33.7	22.2	±	29.9	0.06	0.825	14.3	±	24.5	26.7	±	30.1	-0.45*	0.026
Additional kinetic and kinematic variables																
F_{con} (N.kg^{-1})	13.2	±	2.2	13.3	±	2.9	-0.04	0.870	17.2	±	2.6	15.4	±	2.1	0.77*	<.001
TTT (ms)	831	±	124	814	±	170	0.11	0.659	772	±	143	803	±	162	-0.20	0.312

ISQ_{PF} = maximum isometric force; RSI_{mod} = modified reactive strength index; TO_p = take-off momentum; F_{min} = minimum eccentric force; V_{ecc} = eccentric peak velocity; D_{ecc} = downwards displacement; F_{0V} = force at zero velocity; T_{PF} = timing of peak force; TTT = time to take-off; F_{con} = concentric peak force; AU = arbitrary units; SD = standard deviation; * = $p < 0.05$.

5.4 Discussion

The purpose of this investigation was to determine the influence of maximal isometric strength and the timing of concentric peak force on jump strategy and CMJ performance. The main findings of this study were that 1) when groups were categorised by T_{PF}, significant differences were observed in jump strategy variables but not in CMJ performance; 2) when separated by ISQ strength, strong males and females jumped higher and strong males had a higher RSI_{mod}; and 3) greater ISQ strength significantly affected all jump strategy variables in males, but not in females.

When separated by T_{PF}, significant differences in jump strategies were observed. Both male and female early T_{PF} groups exhibited greater (27-40%) unweighting (lower F_{min}) and a more rapid (23-31%) pre-stretch (higher V_{ecc}), followed by greater (28-31%) SSC preload (higher F_{0V}) than the late T_{PF} groups. These findings partially confirmed the first hypothesis that a jump strategy characterised by lower F_{min} and V_{ecc} (but not D_{ecc}) was associated with an earlier occurrence of peak force in the concentric phase. Similar observations have been previously reported, whereby an earlier peak GRF during the concentric phase of the CMJ was associated with a lower F_{min} and greater F_{0V} (7, 14, 26). Greater unweighting would increase the musculoskeletal system demand to decelerate the downward momentum of the COM, which would likely increase the amount of stored elastic energy in the series and parallel elastic components that could be transferred towards concentric force production. A T_{PF} at or close to amortisation is indicative of a more rapid transition from eccentric to concentric muscle actions, thus potentially limiting energy loss via hysteresis and therefore optimising the SSC. Practitioners seeking to optimise SSC performance are advised to monitor T_{PF} to ensure athletes are effectively transitioning from eccentric to concentric muscle actions.

No significant differences in CMJ performance (jump height, take-off momentum, RSI_{mod}) were observed between early and late T_{PF} groups; therefore, the second part of the first hypothesis was not supported (7, 18). This is somewhat contradictory to recent research which categorised jumps based on the timing of peak force. McHugh et al. (7) reported better jump performance (jump height and RSI_{mod}) when peak force occurred at the transition from eccentric to concentric, compared to later in the propulsion phase. In addition, Bayne et al. (18) reported superior take-off momentum and RSI_{mod} (but not jump height) when peak force occurred within the first 50% of a unimodal CMJ curve or when the first peak of a bimodal jump was greater than the second peak. The results from the aforementioned investigations (7, 18) are supported by previous researchers, concluding that generating larger GRF at the beginning of the concentric phase facilitated improved jump performance (13, 14, 27). The differing results between these investigations and this study may stem from variations in participant instructions. In the prior investigations, participants were cued to "jump as high as possible", whereas participants were instructed to "jump as high and fast as possible" in this study (7, 18). These instructions may have affected participants' preferred jump strategy and, possibly, the relationship between the CMJ force-time series and jump performance (8, 28). Athletes requiring longer contraction times to generate impulse equivalent to those that require shorter times may face challenges in sports or tasks with time constraints. Their performance in activities demanding quick movements or rapid force production might be compromised, potentially affecting agility, reaction time and overall responsiveness (29).

Significant differences were observed for jump height in strong and weak female (13%) and male (9%) groups, while RSI_{mod} was only significantly greater for strong males (13%). The findings of this investigation align with those of the existing literature in its observation that increased maximal strength (dynamic or isometric) is beneficial for jump performance (5, 30-32). Stronger muscles have an increased contractile capacity, thus allowing athletes in the strong groups to generate a larger concentric net impulse and, ultimately, jump higher. Strong males had a significantly greater RSI_{mod} than their weaker counterparts, due to having both increased jump height and shorter TTT (~4%, ES = -0.20, $p = 0.312$); however, no significant differences in RSI_{mod} were observed between strong and weak females. Although strong females jumped higher than weak females, their TTT was longer in duration (~2%, ES = 0.11, $p = 0.659$), thus not increasing RSI_{mod} by a statistical effect. Previous investigations have reported similar TTT values between males and females, suggesting that jump height has a greater influence on RSI_{mod} and speculating that relative strength and jump strategy are underpinning factors (9, 33, 34).

Maximal strength had a significant effect on jump strategy for the male participants in this cohort but not for the females, which allowed only partial confirmation of the second hypothesis. The strong males demonstrated greater unloading (14%), a more rapid pre-stretch (13%), greater SSC preload (14%) and depth (8%) and an earlier (12%) T_{PF} than the weak males. Other investigators have reported similar findings, in that stronger male athletes are able to more effectively unload their bodyweight and generate greater power output and GRF during the initial period of the concentric phase than weaker males (14, 35, 36). Superior strength (especially eccentric strength) would enable a greater capacity for generating braking forces, thus enabling greater decelerations and allowing stronger athletes to perform a more rapid pre-stretch, as they are more capable of decelerating their COM than their weaker counterparts are (14, 37). As for the non-significant differences in jump strategy variables between strong and weak females, previous investigators have reported greater ISQ_{PF} values for females (33.4 $N.kg^{-1}$) than in the current cohort; thus, it could be speculated that the strong female group in this cohort may not accurately represent strong female populations (38). Relative strength has been reported to be an underpinning factor on joint-work distribution, regardless of sex (16), and it could be suggested that a minimum threshold of relative strength may be required to perform, and benefit from, an optimised jump strategy (2).

The results of this investigation indicated that maximal strength was more influential on CMJ performance and jump strategy than T_{PF} was. Practitioners and athletes seeking to improve CMJ performance should prioritise increasing maximal strength over inducing changes in jump strategy or T_{PF}. It may also be speculated that an optimised jump strategy may be adopted after a certain threshold of relative strength has been achieved. However, the results of this investigation are limited to its cross-sectional design; thus, causal relationships cannot be inferred. The relationships between ISQ_{PF} and T_{PF} on CMJ performance and jump strategy may be better understood by monitoring within-athlete changes through longitudinal research. Future researchers should also consider examining jump strategies of females that have elite levels of strength (at least similar to the ISQ_{PF} of the strong males in this investigation) to determine whether sex differences exist at equivalent levels of maximal relative strength.

5.5 Conclusion

This investigation explored the influence of T_{PF} and maximal strength on CMJ performance and jump strategy. The results indicated that T_{PF} might offer valuable insights into an athlete's ability to transition between eccentric and concentric muscle actions, as it appears that early T_{PF} was associated with a distinct eccentric-phase jump strategy, characterised by a more rapid pre-stretch and greater SSC preload. The findings also emphasised the significance of maximal strength in CMJ performance, with stronger individuals displaying superior jump heights. Strong males demonstrated a more rapid eccentric phase and an earlier T_{PF} than their weaker counterparts did; however, no differences in jump strategy were observed between strong and weak females. It was suggested that a specific threshold of maximal strength could be essential to further improve CMJ performance through increased SSC utilisation by optimising jump strategy.

5.6 Chapter summary

This chapter addressed objective 4: determine the association between timing of maximum peak force on eccentric-phase jump strategy parameters and CMJ performance and objective 5: determine the association between lower-limb strength on jump strategy metrics and CMJ performance in 165 athletes from a variety of different sports. The findings of this chapter revealed that an early T_{PF} was associated with a jump strategy characterised by greater unloading of bodyweight, a more rapid pre-stretch and greater SSC preload for both female and male athletes. However, no significant differences in CMJ performance measures were observed between early and late T_{PF} groups. While maximal strength significantly affected jump height, RSI_{mod}, jump strategy and T_{PF} in males, its influence was less pronounced in females. It was speculated that the strong female participants were not accurate representatives of strong female populations.

Although the findings in Chapter 4 highlighted the relationships between eccentric-phase jump strategy variables and CMJ performance, the findings of Chapter 5 would suggest that maximal strength is more influential on CMJ performance than jump strategy or T_{PF}, emphasising the importance of prioritising strength training to improve jump performance. However, the combination of both increased strength and optimised jump strategy was suggested to produce the most desirable outcome for CMJ performance improvement. Moreover, longitudinal research is needed to understand the causal relationships between jump strategy and CMJ performance. Building on the insights gained in the previous chapters, Chapter 6 investigates the longitudinal influence of a training intervention aimed at altering jump strategy to optimise the SSC mechanism and, ultimately, improve CMJ performance.

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Chapter 6: Attenuated eccentric loading elicits changes in countermovement jump strategy

Abstract

This study aimed to investigate the influence of an attenuated eccentric loading intervention on jump strategy and countermovement jump (CMJ) performance. Forty-two female (n = 22) and male (n = 20) collegiate hockey players underwent a six-week training programme, with a subgroup from each sex performing normal CMJs while the other subgroup performed assisted CMJs with 20% bodyweight reduction. Ground reaction force data during the CMJ and isometric squat (ISQ) assessments were captured on three separate occasions. Within the intervention groups, significant differences were observed in jump strategy metrics, including unloading of bodyweight (8.1-8.3%), eccentric peak velocity (7.2-8.9%) and braking impulse (9-13.9%), with moderate to large effect sizes (ES < -0.40). However, CMJ performance and strength measures remained unchanged and no significant between-group differences were observed. It was theorised that changes in jump strategy would lead to improvements in CMJ performance through optimisation of the stretch-shorten cycle (SSC). However, it was speculated that a certain level of maximal strength is essential to benefit from the SSC mechanism, as greater decelerations demands are required when utilising a more eccentrically rapid jump strategy.

6.1 Introduction

Training interventions are implemented with the intent of developing specific adaptations that will either improve athletic performance or reduce the risk of injury. Changes in countermovement jump (CMJ) performance are often used to determine the efficacy of training interventions that target lower-body performance, as the CMJ is considered a valid and reliable measure of lower-body power (1). Recently, researchers have become interested in the manner in which an athlete moves their centre of mass (COM) through the eccentric and concentric phases of a CMJ, which has been referred to as jump strategy (2, 3). The importance of jump strategy has been highlighted as eccentric-phase jump strategy has a direct influence on concentric force output and an indirect influence on CMJ performance (2-5). Many researchers have determined the efficacy of a training intervention by solely monitoring changes in CMJ performance; however, less is known about how jump strategy is influenced by various training interventions.

The analysis of the vertical ground reaction force (GRF) produced during a CMJ can provide information pertaining to jump strategy in areas such as acceleration, velocity and displacement, which are derived from the force-time data series (3, 6). Analysis of jump strategy allows practitioners to identify how effective an athlete is at utilising the stretch-shorten cycle (SSC). The coupling of eccentric and concentric muscle actions is referred to as the SSC, and the inclusion of eccentric movement (pre-stretch) in exercise allow muscles to develop a higher active state , thereby enhancing initial concentric force output, compared to an exercise that is not immediately preceded by a pre-stretch (7). Initiating the concentric phase with a greater GRF would contribute to increased concentric impulse, thereby increasing CMJ performance (7). The performance-enhancing effects of the SSC are also influenced by the amount of force that is applied on tendons and muscles prior to concentric movement (SSC preload) (7). Elastic potential energy can be stored in tendons and muscles during eccentric movement and then be reutilised to increase initial concentric force production (7). However, a delayed transition from eccentric to concentric movement may cause the stored elastic energy to dissipate as heat and reduce the performance-enhancing effects of the SSC (8). An efficient or rapid transition from eccentric to concentric muscle actions can be identified when peak GRF coincides with the moment between these muscle actions (amortisation) or early in the concentric phase, as previous investigations have reported associations between the timing of peak force and jump performance (3, 5, 9).

Jump strategies characterised by greater unloading of bodyweight and increased braking GRF have been associated with an earlier occurrence of peak GRF, indicating an efficient SSC. For example, Cormie et al. (5), Kijowski et al. (10) and Hoffman et al. (9) aimed to quantify changes in jump strategy variables after implementing plyometric and resistance training or Olympic weightlifting training interventions. These authors attributed the increases in jump performance partially to a more efficient use of the SSC mechanism due to the increased pre-stretch velocities and increased braking GRF during the eccentric phase of the CMJ from pre- to post-intervention assessments (5, 9). However, the combination of modalities utilised in these investigations (ballistic exercises alongside high-intensity resistance training) has made it difficult to deduce which modality had a greater influence on the changes in jump strategy (5, 9, 10). Other investigations have examined the influences of CMJ variations on jump strategy, including dumbbell-accentuated loaded jumps (11), loaded CMJs (12), verbal cueing (13), band assisted and resisted jumps (14, 15). However, the longitudinal influence of these exercises on jump strategy was not investigated (11, 13-15). It is crucial to determine whether the intended training outcome of an exercise is adopted by the athlete, thereby ensuring its long-term efficacy.

There is growing interest in understanding movement strategies that underpin performance in order to inform individualised training interventions (2-4, 6). Although several interventions to improve jump height have been described, the methods of training for a more efficient jump strategy are not well studied. Therefore, the aim of this study was to quantify changes in jump strategy through an attenuated eccentric loading exercise intervention. It was hypothesised that 1) the intervention group would adopt a more rapid eccentric velocity, greater SSC preload, and earlier time to peak GRF jump strategy compared to the control group; and 2) the intervention group would improve jump performance more than the control groups would.

6.2 Materials and methods

6.2.1 Participants

A total of 42 athletes (female: n = 22, height = 1.63 ± 0.05 m, mass = 61.6 ± 6.5 kg, age = 21.3 ± 0.8 yr, maximum isometric force - ISQ_{PF} = 22.7 ± 5.5 N.kg^{-1}; males n = 20, height = 1.72 ± 0.06 m, mass = 75.2 ± 6.0 kg, age = 21.6 ± 1.2 yr, ISQ_{PF} = 27.2 ± 5.5 N.kg^{-1}) volunteered and provided written informed consent to participate in this study. All participants had completed at least six months of supervised resistance training (two to three sessions per week) followed by a two-week transition phase prior to this study. None of the participants reported any injuries at the time of testing and all competed at a collegiate level of competition in field hockey. All participants were over the age of 18 and did not require parental consent to participate in this study. Ethical approval was granted by the Faculty of Health Sciences Research Ethics Committee (771/2020).

6.2.2 Procedures

All participants attended the laboratory on three separate occasions (Figure 6.1) where CMJ and isometric squat (ISQ) data were collected. The participants were asked to refrain from performing resistance exercise for 72 hours prior to each testing session and to wear the same footwear and similar clothing for both testing occasions. After completing the first testing session, participants were then separated into two matched-pair groups based on their jump height. Both groups completed identical training programmes; however, the intervention group was prescribed assisted (20 ± 3% BW) CMJs as the intervention exercise to supplement their training programme, while the control group were assigned normal CMJs. A pilot study (Appendix D) found that the assisted CMJ exercise best optimised jump strategy and improved CMJ performance compared to other CMJ variations. Participants were reassessed after the six-week training block. A third testing session was conducted after a two-week tapering period to account for any effects of training fatigue elicited during the six-week training programme.

Figure 6.1 Outline of assessment and training schedule

6.2.2.1 CMJ

Every participant completed a standardised warm up, including three sub-maximal CMJs with increasing intensity for each jump. All participants were familiar with the CMJ testing protocol and had previously performed CMJs as part of a routine athlete-monitoring programme. Participants were asked to stand on the dual force platform (JM6090-06, Bertec, USA) with one foot on each plate. Participants stood still prior to initiating the first CMJ to allow determination of bodyweight for post-testing analysis and then performed three CMJs (with between 30 and 60 seconds of rest between each jump) with their arms akimbo to eliminate the use of arm swing. Participants were instructed to "jump as high as possible, as fast as possible" and to "maintain full extension during the flight phase until the moment of touchdown" and countermovement depth was not controlled. A CMJ trial was repeated if the participant removed their hand/s from their hips when performing a CMJ and/or did not land on the platform with both feet. After the participant completed the three CMJ trials, a five-minute rest period was allocated before initiating the ISQ testing.

6.2.2.2 ISQ

The ISQ trials were completed on the same dual force plates, surrounded by a custom-built squat rack fitted on either side of the plates. An immovable bar was placed inside the rack at the height required to achieve a knee and hip flexion angle of 60^0 (measured with a goniometer) for each participant (16). The participants were instructed to place a foot on each platform directly under the bar (with a similar stance required for the CMJ trials) and stood still prior to initiating the first ISQ to allow determination of body weight for post-testing analysis. Participants were instructed to push upwards against the bar with maximal effort without the use of their arms. Each participant was required to complete three trials with maximal effort. The duration of each trial was three seconds with between 30 and 60 seconds of rest between trials. A trial was repeated if the participant did not maintain contact with the bar throughout the trial, did not sustain maximal effort throughout the trial, and/or maintain maximal effort for the full three seconds.

6.2.3 Data collection and analysis

Ground reaction force data was sampled at 1000 Hz and recorded using ForceDecks software (VALD Performance, Australia). Force and time data were recorded for each CMJ and ISQ trial and variables of interest were calculated from the force-time record. Jump height was calculated using COM take-off velocity, which was determined through the impulse-momentum method (17). The data were exported to Microsoft Excel (version 16.16.27) for data cleaning. The variable TO_p was calculated as the product of take-off velocity and body mass using Microsoft Excel, as ForceDecks did not provide this variable.

CMJ phases were defined by previously established criteria (18, 19). The first CMJ phase was the weighing phase, where the participant was asked to stand completely still on the force platforms for at least one second to record body weight (BW) and eliminate signal noise prior to initiating the CMJ (19). The eccentric phase was divided into two distinct phases: the unweighting and braking phases. The initiation of the unweighting phase was identified when the vertical force decreased by a threshold of 20 N less than the participant’s body weight. The braking phase began from the moment after peak negative velocity to the moment negative COM velocity equalled zero (which coincided with the lowest depth of the countermovement). The propulsion phase began when the participant’s upwards COM vertical velocity increased above a threshold of 0.01 $m.s^{-1}$ (19) and ended when the participant was no longer in contact with the force platform and had entered the flight phase of the CMJ, based on a threshold of 30 N. Displacement (D_{ecc}) and velocity (V_{ecc}) in the downwards direction were considered negative. All force metrics, including F_{min}, F_{0V} and braking impulse ($I_{braking}$), were reported as net force values (GRF – BW) and normalised to body mass ($N.kg^{-1}$). The metric $I_{braking}$ was calculated as the area under the force-time graph between V_{ecc} and initiation of the concentric phase. Time to take-off (TTT) was included in the descriptive statistics, as it is a component required for the calculation of RSI_{mod}.

6.2.4 Training programme

Both control and intervention groups completed identical warm-up protocols, involving a five-minute low-intensity (heart rate zones 1-2) cardiovascular warm up on an ergometer of their choice, followed by a dynamic warm up consisting of bodyweight squats (two sets, 10 repetitions), lunges (one set, 10 repetitions), ankle-banded shuffles (one set, 10 repetitions each leg) and submaximal CMJs (one set, three repetitions). Participants were allowed to perform static or dynamic stretches (based on personal preference) after completing the dynamic warm up, as previous investigations reported trivial increases and/or decreases in CMJ performance as a result of static or dynamic stretching prior to performing CMJs (20, 21).

The training programme utilised a high volume (1 284 ground contacts) and low-intensity plyometric design with two training sessions per week (Mondays and Thursdays between 17:00 and 19:00) for six weeks. A rising undulating volume scheme was utilised, with the load scheme presented in Table 6.1. Both groups (intervention and control) completed the same training programme; however, the intervention group performed an attenuated eccentric loading protocol using band assisted CMJs, whereas the control group performed normal CMJs to avoid discrepancies in training volume. The tension of the bands used by the intervention group was set at a 20 ± 3% reduction of the participant's bodyweight (when standing during the weighing phase) as recommended by a previous investigation (15). A pilot study (Appendix D) found the 20% reduction in bodyweight sufficient to elicit changes in jump strategy and that the assisted CMJ exercise best optimised jump strategy and improved CMJ performance compared to other CMJ variations.

Traditionally, rest for training allocated using the phosphagen energy system is a 1:12 work to rest ratio. However, previous investigations have indicated that plyometric exercises performed with low repetitions (completed in under 10 seconds) can use a shorter rest period between sets (1:5-9 work to rest ratio or 45 to 90 seconds) (22).

Participants in both control and intervention groups were instructed to "jump as high and explosively as possible", as this cue has previously been reported to elicit increases in eccentric peak velocity while maintaining concentric mean and peak power output when compared to self-selected countermovement velocities (13). Familiarisation for both assisted and normal CMJ was conducted prior to the initiation of the intervention and the technique of each participant was evaluated to minimise risk of injuries.

Table 6.1 Six-week ballistic training programme

		Session A			**Session B**		
Week	**Exercise**	**Sets**	**Reps**	**Rest (s)**	**Sets**	**Reps**	**Rest (s)**
1	CMJ	5	10	90	7	10	90
	RCMJ	3	6	30	4	6	30
2	CMJ	6	10	90	8	10	90
	RCMJ	3	8	35	4	8	35
3	CMJ	7	10	90	9	10	90
	RCMJ	3	10	40	4	10	40
4	CMJ	5	10	90	7	10	90
	RCMJ	3	6	30	4	6	30
5	ASL CMJ	3	20	90	5	20	90
	RCMJ	3	12	50	4	12	50
6	ASL CMJ	4	20	90	6	20	90
	RCMJ	3	15	60	3	15	60

CMJ = countermovement jump, RCMJ = repeated countermovement jump, ASL = alternating single leg

6.2.5 Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics (Version 27) for Windows. The interquartile rule was used to identify and remove outliers, with observations lower than the first quartile minus 1.5 times the interquartile range or those above the third quartile plus 1.5 times the interquartile rule were considered to be outliers. Data were presented as means and standard deviations to represent centrality and spread of data. Normality was assessed using the Shapiro-Wilk test, with an alpha level set at 0.05, where a p value greater than 0.05 indicated that the data were normally distributed. A repeated-measures analysis of variance (ANOVA) was conducted to examine the impact of training on jump performance and strategy variables at both baseline and post-test for each group. An independent T-test (Welch's for different sample sizes) was conducted to ensure there were no statistically significant ($p < 0.05$) differences in CMJ metrics between groups at baseline. Another T-test was conducted at post-test to determine the magnitude of the differences between groups, and the strengths of the values were selected based on the standards used by previous investigations (4, 23) and interpreted as trivial (≤0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (2.0–4.0) (24). The statistical significance threshold was set a priori at $\alpha = 0.05$ for both the ANOVA and independent T-test.

6.3 Results

The means, standard deviations (SD), within-subject differences ($\Delta\%$) and effect sizes for CMJ variables of interest for females are presented in Table 6.2, and those for males in Table 6.3. The mean compliance rate for the number of training sessions attended was 85% (10 out of 12 training sessions; female 83% and male 87%). Three females (two from the control group and one from the intervention group) and two males (both intervention) were excluded from the final analysis due to non-completion of the training programme. The preliminary T-test analysis confirmed that there were no significant ($p > 0.05$) differences between the control and intervention groups at pre-training for all variables.

With regards to the jump strategy measures, the within-group changes over the training intervention for the control group across both sexes were non-significant, and all training effects were trivial or small, with the exception of V_{ecc} in males (ES = -0.61). However, significantly different pre-post comparisons within the intervention group were observed for $I_{braking}$ (ES = 0.1.32 and 1.03), V_{ecc} (ES = -1.21 and -1.30) and F_{min} (ES = -0.77 and -1.20) for female and male athletes respectively.

In terms of CMJ performance and strength measures, the within-group changes over the training intervention for the control group across both sexes were non-significant, and all training effects were trivial or small. The results of the within-group comparisons for the intervention group were similar ($p > 0.05$), with all effect sizes trivial or small, except for TO_p in females (ES = 0.65).

No significantly different between-group comparisons were observed in any measure, and all effects were trivial or small, with the exception of moderate improvements noted in the $I_{braking}$ of females (ES = -0.61) and V_{ecc} of males (ES = -0.62).

Table 6.2 Comparison of CMJ variables for female participants

	Control (n = 9)						Intervention (n = 10)							Control vs. intervention	
	Pre		Post		Within-subject Post-Pre		Pre		Post		Within-subject Post-Pre				
	Mean	SD	Mean	SD	Δ%	d	Mean	SD	Mean	SD	Δ%	d		Δ% difference	d
T_{PF} (%)	20.5	27.4	14.4	25.4	-6.1	-0.19	21.8	25.1	24.6	35.3	2.8	0.08		-8.6	0.26
ISQ_{PF} (N.kg^{-1})	22.4	5.5	22.7	5.2	0.9	0.17	23.0	6.1	24.0	5.7	4.5	0.37		3.6	-0.34
D_{ecc} (cm)	-26.8	5.2	-26.9	4.0	-0.3	-0.02	-27.5	5.0	-30.9	7.3	4.4	-0.34		4.6	-0.17
F_{OV} (N.kg^{-1})	13.6	3.6	14.3	2.8	4.2	0.24	12.3	3.4	12.8	2.9	0.3	0.12		-3.9	0.14
$I_{braking}$ (N.s.kg^{-1})	1.07	0.22	1.17	0.20	7.6	0.51	1.06	0.12	1.27	0.19	15.9	1.32	*	8.3	-0.61#
V_{ecc} (m.s^{-1})	-1.07	0.19	-1.17	0.20	7.5	-0.54	-1.07	0.13	-1.27	0.19	14.7	-1.21	*	7.2	-0.56
F_{min} (N.kg^{-1})	-5.75	2.02	-6.33	1.75	8.5	-0.36	-5.37	2.38	-7.47	1.52	17.5	-0.77	*	9.0	-0.41
TTT (ms)	749	129	700	81	-7.4	-0.39	764	119	744	126	-6.2	-0.11		1.2	-0.05
Jump Height (cm)	29.5	3.0	30.5	3.5	3.0	0.51	29.0	3.9	29.4	4.2	1.2	0.24		-1.8	0.28
RSI_{mod} (AU)	0.42	0.08	0.44	0.08	5.0	0.31	0.39	0.10	0.41	0.12	2.6	0.21		-2.4	0.09
TO_p (kg.m.s^{-1})	145	16	148	17	1.7	0.52	146	11	149	12	1.8	0.65	*	0.1	-0.03

* = $p < 0.05$ from pre- to post-training; # = $p < 0.05$ between groups; AU = Arbitrary Units; ISQ_{PF} = maximum isometric force relative to body mass.

Table 6.3 Comparison of CMJ variables for male participants

	Control (n = 10)						Intervention (n = 8)							Control vs. intervention	
	Pre		Post		Within-subject Post-Pre		Pre		Post		Within-subject Post-Pre				
	Mean	SD	Mean	SD	Δ%	d	Mean	SD	Mean	SD	Δ%	d		Δ% difference	d
T_{PF} (%)	18.7	19.1	19.3	17.8	-1.6	-0.10	19.5	25.0	13.3	23.0	-6.2	-0.39		-4.6	0.30
ISQ_{PF} (N.kg^{-1})	27.6	5.6	26.9	4.5	-2.9	-0.07	27.5	6.1	27.6	6.9	-1.4	0.01		1.5	-0.11
D_{ecc} (cm)	-29.0	6.0	-30.6	6.1	6.2	-0.36	-28.5	7.4	-33.1	6.2	11.6	-0.51		5.4	-0.24
F_{OV} (N.kg^{-1})	15.4	2.81	15	3.32	-4.2	-0.08	17.2	5.1	16.4	3.0	-6.4	-0.15		-2.2	0.08
$I_{braking}$ (N.s.kg^{-1})	1.14	0.26	1.27	0.30	8.2	0.51	1.20	0.23	1.47	0.19	16.3	1.03	*	8.1	-0.49
V_{ecc} (m.s^{-1})	-1.13	0.26	-1.24	0.28	9.9	-0.61	-1.19	0.24	-1.47	0.19	18.8	-1.30	*	8.9	-0.62#
F_{min} (N.kg^{-1})	-6.0	2.2	-6.5	2.1	6.4	-0.32	-6.1	1.3	-7.9	1.4	20.3	-1.20	*	13.9	-0.42
TTT (ms)	754	154	761	121	0.3	-0.01	715	120	700	83	-3.2	-0.10		-3.5	0.19
Jump Height (cm)	40.9	6.1	40.6	3.9	0.7	0.06	41.7	4.4	43.5	4.2	3.9	0.40		3.2	-0.33
RSI_{mod} (AU)	0.54	0.11	0.53	0.11	-1.3	-0.05	0.59	0.09	0.62	0.09	1.9	0.18		3.2	-0.20
TO_p (kg.m.s^{-1})	218	17	220	13	-0.4	-0.07	216	33	220	31	2.1	0.36		2.4	-0.51

* = $p < 0.05$ from pre- to post-training; # = $p < 0.05$ between groups; AU = Arbitrary Units; ISQ_{PF} = maximum isometric force relative to body mass.

6.4 Discussion

The purpose of this investigation was to determine if an attenuated eccentric loading exercise intervention affected measures of jump performance, strength and jump strategy. It was hypothesised that the training intervention would induce changes to jump strategy and ultimately CMJ performance. The main findings of this study were: 1) statistically significant within-group jump strategy changes were noted in the intervention group of both sexes for F_{min}, V_{ecc} and $I_{braking}$, with the effect sizes ranging from moderate to large; 2) within-group changes in jump performance and strength measures were mostly trivial or small and non-significant ($p > 0.05$), with the exception of TO_p in the female intervention group (ES = 0.65); and 3) no significant between-group differences in CMJ performance were observed for either sex.

In both intervention groups (male and female), significant changes in F_{min} (~19%), V_{ecc} (~17%) and $I_{braking}$ (~16%) were observed; however, no changes ($p < 0.05$) were noted in D_{ecc}, F_{0V} or T_{PF}. These findings suggest that the intervention groups adapted their unweighting strategy by increasing downward acceleration and velocity, necessitating greater braking impulses. However, despite these changes, F_{0V} remained unchanged, indicating a potentially longer time required to decelerate their COM, likely resulting in greater D_{ecc} and contraction duration. Therefore, changes in strategy did not lead to increased optimisation in the SSC outcome metrics (25). Non-significant changes in eccentric peak force (which occurs just prior to F_{0V}) were reported in a similar study conducted by Markovic et al. (26), which may suggest that the influence of assisted CMJs on jump strategy is limited to the unweighting phase. Using combined training modalities of high-intensity resistance training alongside ballistic exercises, previous research reported similar changes in F_{min} and V_{ecc} as those observed in this study; however, increases in F_{0V} and an earlier shift in the occurrence of peak force were also reported (5, 9, 10, 27). The combination of these two training modalities could simultaneously promote increases in both maximal force production through resistance training and movement velocity via ballistic exercises (28, 29). Additionally, maximum strength has been suggested to be an underpinning quality required for effective decelerations and may have allowed the athletes in these studies to adopt a jump strategy that resulted in increases in F_{0V}, allowing for a more effective use of the SSC (5, 9, 10, 27, 30).

The training protocols used for both control and intervention groups did not produce significant longitudinal changes in CMJ performance and, as a result, no significant interaction effect was observed between groups. This finding contradicts those of previous researchers, who reported notable increases in jump height with assisted training. For example, Argus et al. (15) reported a 6.7% (ES > 0.2; $p < 0.05$) increase in jump height in professional rugby players over a four-week training period using a 20% reduction in BW. Markovic et al. (26) documented a 7.9% (ES = 0.86; $p < 0.02$) increase in jump height across a seven-week intervention. These researchers employed a 30% reduction in BW during their intervention, which may have provided a more effective stimulus to promote positive neuromuscular adaptations (26). It is worth noting that while the study conducted by Markovic et al. (26) involved participants with comparable jump ability to those in the current investigation, they may have had more exposure to vertical jumping relative to the field hockey player cohort in this investigation, potentially influencing the effectiveness of the intervention. Finally, Sheppard et al. (31) reported a 4.2% (ES = 0.21; $p < 0.01$) increase in jump height over five weeks among elite junior volleyball players utilising a ~12% reduction in BW. Although a lower reduction in BW was implemented in the aforementioned investigation, the athletes already possessed superior jump ability (61 ± 6 cm) prior to initiating the intervention (31). The aforementioned researchers also reported varying findings of non-significant (26), small (15), and large (31) differences in jump performance when comparing assisted CMJ groups to the control groups. The differing jump performance outcomes across studies may stem from variations in maximal strength among cohorts; however, the researchers in these studies did not provide details regarding their participants' maximal strength qualities (15, 26, 31). It has been proposed that stronger athletes benefit from optimised jump strategies sooner than weaker athletes do (5, 9). It may be speculated that the athletes in this investigation did not possess sufficient strength to benefit from changes in jump strategy within the time frame provided (5, 15, 27). This contention is somewhat supported by observations from data collected in the researchers’ own lab, where the male cohort in this investigation would be considered as a ‘weaker’ population.

Several limitations of this study warrant consideration. Firstly, the observed changes in jump strategy may be specific to field hockey players, whereas implementing the training protocol used in this study in other sporting populations may induce varied responses. Moreover, the force orientation in field hockey is predominantly horizontal, which does not necessarily translate to vertical jump performance (32). Secondly, it is possible that the cohort in the current investigation did not possess a sufficiently high level of relative strength to benefit from the observed alterations in jump strategy and improve CMJ performance. Previous investigations have suggested that individuals with superior strength capabilities but slower movement velocities may benefit from implementing assisted CMJs in their training programmes. Lastly, the exclusion of high-intensity training (aimed at increasing maximal strength) in the current study may have limited the training effects of the assisted CMJ exercise, as previous researchers have observed significant changes in jump strategy and increases in jump height when combining ballistic exercises and high-intensity resistance training modalities (5, 9).

6.5 Conclusion

The attenuated eccentric loading protocol resulted in an altered CMJ strategy involving greater unweighting. However, deceleration capability did not improve and so SSC outcome metrics were not enhanced. As a result, this study did not observe significant improvements in CMJ performance from the training protocols implemented for both control and intervention groups. This observation differs from those of previous researchers, who have documented practically relevant increases in jump height through assisted CMJ interventions. It is proposed that maximal strength improvements may be required to effectively utilise a strategy with greater downwards acceleration and velocity to enhance CMJ performance. While assisted CMJs offer potential benefits, particularly altering jump strategy during the unweighting phase, a more comprehensive approach incorporating high-intensity resistance training may therefore be needed to fully harness the benefits of the altered SSC. Assisted exercises offer a unique stimulus promoting neuromuscular adaptations and have previously shown promise in enhancing jump and sprint ability; however, the findings of this investigation highlight the need for a nuanced approach when designing training programmes for specific sports and individual athletes.

6.6 Chapter summary

This chapter addressed objective 6: to evaluate the effects of a training intervention programme using the results gathered from studies 1-3 to improve CMJ strategy and performance in 42 female and male collegiate hockey players. While significant within-group changes in jump strategy were observed for the intervention groups, no significant improvements in CMJ performance were noted when compared to the control groups. The findings suggest that while the intervention altered jump strategy by promoting greater unloading of bodyweight, eccentric peak velocity and braking impulse, it did not lead to increases in jump height, RSI_{mod} or TO_p.

Previous investigations that tested the effect of training interventions on jump strategy and CMJ performance did so using a combination of training modalities (ballistic and resistance training). Although significant improvements in CMJ performance and changes in jump strategy were reported, it was unclear which training modality had a greater influence on these changes. This study tested the effect of a single training modality to elucidate whether changes in jump strategy were a result of ballistic exercises or changes in maximal strength. It was speculated that, while assisted CMJs may alter jump strategy, improvements in maximal strength may be necessary to fully realise performance enhancements. These findings underscore the importance of tailored training programmes for optimising athletic performance. In Chapter 7, the findings from Chapters 3 to 6 will be synthesised and discussed within the context of the surrounding literature.

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Chapter 7: General Discussion

Jump strategy has become a topic of interest in contemporary literature surrounding the countermovement jump (CMJ) (1-3). The term 'jump strategy' describes the manner in which an athlete moves their centre of mass (COM) throughout the CMJ and can be derived from the analysis of ground reaction force (GRF). Analysing jump strategy has presented an opportunity to monitor how effective an athlete is at utilising the performance-enhancing effects of the stretch-shorten cycle (SSC). The rapid coupling of eccentric and concentric muscle actions is referred to as the SSC and allows for generation of an active state during eccentric movement, contributing towards additional concentric GRF production (4). However, limited information currently exists regarding jump strategy and its relationship with measures of CMJ performance. Moreover, maximal strength has been well documented as an underpinning factor for CMJ performance and the associations between maximal strength and jump strategy are yet to be thoroughly established (5, 6). The aim of this thesis was to evaluate alternative measures of SSC utilisation, investigate the influence of lower-body physical characteristics, and test the effect of a training intervention informed by traditional and novel diagnostic measures to improve countermovement jump strategy and performance. To achieve this aim, a series of chapters (comprising a literature review, three experimental investigations and a training intervention) were conducted. Chapter 7 aims to contextualise the research conducted in this thesis, synthesise the findings from the previous chapters, and discuss their implications within the existing literature.

7.1 Overview

The topic of this thesis was introduced in Chapter 1, along with the motivations and objectives, from which six objectives were identified. Chapter 2 provided a brief review of the relevant literature surrounding the topic of this thesis, including the relationships between maximal strength and jump performance, the SSC and CMJ training modalities.

Examining the variability and consistency of diagnostic measures of CMJ performance and jump strategy metrics derived from ground reaction force data during the CMJ in Chapter 3 was important to determine the confidence with which these variables could be used in the following chapters. Some measures showed acceptable variability while others did not, particularly within the eccentric phase and especially ratio variables. The findings of Chapter 3 underscore the need for careful selection of diagnostic metrics and informed interpretation before providing immediate feedback to the athletes.

The objectives introduced in Chapter 4 sought to determine the relationship between eccentric-phase biomechanical parameters and CMJ performance through correlational and stepwise regression analysis. The results of this experiment revealed that eccentric-phase parameters – specifically unloading of bodyweight, downwards displacement, eccentric peak velocity and force at zero velocity (SSC preload) – held significant value for maximising CMJ performance, thus providing a rationale for monitoring and analysing changes in jump strategy resulting from training adaptations.

The aims of Chapter 5 were to determine the influence of (i) the timing of peak force within the concentric phase and (ii) maximal strength on jump strategy and CMJ performance. While the timing of peak force showed associations with jump strategy, differences in CMJ performance were more pronounced between weaker and stronger athletes. Furthermore, differences in jump strategy were observed between strong and weak males, but not in their female counterparts. The findings of this chapter shed light on the nuanced interactions between strength and jump strategy.

The information gathered in Chapters 3-5 was used to design a training intervention targeted at altering eccentric-phase jump strategy and improving CMJ performance. Chapter 6 detailed a six-week training programme involving two groups of both females and males. One group from each sex served as a control, performing normal CMJs, while the other underwent an intervention, performing assisted CMJs. The findings revealed that jump strategy during the unweighting phase changed for the intervention group; however, these changes did not induce improvement in CMJ performance.

7.2 Synthesis

The variability of the CMJ performance and jump strategy metrics of interest observed in Chapter 3 aligned with those reported by previous investigators (3, 7, 8). Jump height and concentric-phase variables (including power, impulse and peak velocity) have been extensively assessed for their variability and have consistently shown acceptable variability across investigations (3, 9). Although little attention has been given to assessing the variability of eccentric-phase variables, growing interest in monitoring jump strategy has led to an increased number of investigations reporting the variability of eccentric-phase variables (7, 8). The findings of Chapter 3 revealed that eccentric-phase kinematic variables (including eccentric peak velocity and downwards displacement) had more acceptable variability than kinetic variables such as unloading of bodyweight and eccentric braking impulse (but not eccentric peak force). Previous investigations have observed improved variability when analysing kinetic variables such as unloading of bodyweight and braking impulse relative to bodyweight (1, 3). Practitioners providing feedback to athletes regarding CMJ performance and concentric-phase variables should do so with confidence, but exercise caution around immediate feedback on eccentric-phase variables until thorough analysis has been completed. The current investigation examined the variability of ‘novel’ variables created in an attempt to quantify SSC utilisation by creating a quotient between eccentric and concentric using power, impulse and work metrics (10). Comparing eccentric- and concentric-phase parameters as a ratio may indicate the storage and release of elastic energy in the SSC. However, these ratio variables had unacceptable variability and did not instil confidence in their use in the short or long term. Coaches and sport scientists often seek efficiency when analysing performance. However, caution is advised when creating new metrics, as urgency and novelty should not outweigh reliability.

The velocity and amplitude of the pre-stretch is believed to have an indirect influence on CMJ performance by affecting SSC preload, thereby enhancing the performance effects of the SSC. This belief is supported by the findings of Chapter 4. Larger downwards displacement (amplitude) was observed to correlate most strongly (r = 0.27-0.37) with jump height (compared to other jump strategy metrics), a finding which is consistent with prior research (1, 11, 12). Take-off momentum (take-off velocity scaled to body mass) is a performance metric that allows practitioners to monitor the jump performance of an athlete while factoring in fluctuations or changes in the athlete's mass over time. The correlations observed between take-off momentum and unloading of bodyweight ($r = 0.37$-0.62) in Chapter 4 were similar to those reported by Harry et al. (1) ($r = 0.34$). Practitioners and athletes aiming to maximise take-off momentum are advised to increase unloading of bodyweight. The modified reactive strength index was proposed to quantify ballistic ability and SSC utilisation, as it factors a temporal element in its calculation but still lacks details regarding velocity and amplitude exhibited during the pre-stretch (13, 14). However, the findings from Chapter 4 revealed strong correlations ($r = 0.70$-0.72) between SSC preload and RSI_{mod}, similar to those reported by Barker et al. (15) and Harry et al. (1). This finding lends support to RSI_{mod} in that it may provide some indication of how effective an athlete is at utilising the SSC. Practitioners interested in monitoring changes in RSI_{mod} should include SSC preload as part of their analysis due to their strong relationship. However, the results from the stepwise regression analysis revealed that a combination of jump strategy variables – particularly downwards displacement, eccentric peak velocity, unloading of bodyweight and SSC preload – are crucial for maximising CMJ performance (jump height, RSI_{mod} and take-off momentum). Although each CMJ performance metric had a moderate to large correlation ($r > 0.27$-0.72) with a specific jump strategy variable, practitioners should consider taking a holistic approach to the jump strategy metrics to improve all aspects of jump performance.

Recently, investigators have become interested in analysing the timing of peak force (T_{PF}) relative to the moment of transition from eccentric to concentric muscle actions, as it may indicate how effective an athlete is at maximising the benefits of the SSC mechanism (16, 17). A T_{PF} occurring at amortisation or early in the concentric phase is indicative of an efficient and rapid transition from eccentric to concentric muscle actions with minimal loss of elastic energy. In Chapter 5, athletes who generated a T_{PF} early in the concentric phase were observed to have a different jump strategy than those who generated a later T_{PF}. Both female and male athletes that exhibited an earlier T_{PF} had significantly ($p < 0.05$) greater unloading of bodyweight, eccentric peak velocity and SSC preload than the late T_{PF} group. Previous investigators have reported similar trends in jump strategies to those of the findings in Chapter 5, including the non-significant differences ($p > 0.05$) in downwards displacement between groups separated by occurrence of peak force (16, 18, 19). However, despite the differences in jump strategies, both groups achieved similar CMJ performances, contradicting the findings of previous investigations (16, 17). The variation in results across studies may be due to the differing participant instructions. In the current research, participants were instructed to prioritise urgency during the CMJ, whereas participants in the other research were not (16, 17). The findings of Chapter 5 could imply that there may be multiple effective techniques for generating force in the CMJ to achieve optimal jump performance. Practitioners could explore and adapt different movement strategies based on individual preferences and external constraints (20) without compromising performance outcomes.

An investigation into the influence of maximal strength on CMJ performance and jump strategy was also included in Chapter 5. It was observed that stronger athletes had a greater jump height than weaker athletes did; however, significant differences in RSI_{mod} ($p < 0.001$; $d = 0.68$) were only significantly greater for strong males. It is well understood that increased maximal strength enables improved athletic performance, with the findings of Chapter 5 continuing to support this. However, the differences in RSI_{mod} are more likely related to the observed differences in jump strategies between strong and weak females and males. Strong males were observed to have a greater unloading of bodyweight, eccentric peak velocity, downwards displacement, SSC preload, and earlier T_{PF} than weak males were. Similar observations have been previously reported, where stronger athletes (specifically males) generated greater power output and GRF at the initiation of the concentric phase than weaker athletes did while adopting jump strategies similar to those of the strong males observed in Chapter 5 (18, 21, 22). Although no significant differences in the time taken to complete the CMJ (time to take-off) were observed between strong and weak groups, the jump strategy utilised by the strong males contributed to a shorter time to take-off, allowing RSI_{mod} to be greater by a statistical effect compared to weak males, whereas strong females had a longer time to take-off than their weaker counterparts did. The non-significant differences between strong and weak females may be due to a lack of either timing and coordination of joint sequencing, which could be adjusted with verbal cues (23), or a minimal threshold of relative strength (6). Previous authors have suggested that individuals with lower levels of strength have a reduced capacity to perform, and benefit from, a more optimised jump strategy (6). The findings from Chapter 5 would suggest that increased maximal strength is more beneficial for CMJ performance than jump strategy; however, the combination of increased maximal strength and an optimal jump strategy generates superior jump performance overall.

Chapter 6 presented an opportunity to bridge the gap between research and application in the form of a training intervention to determine the influence of a ballistic exercise on jump strategy, CMJ performance and strength metrics. Before the initiation of the training intervention, a pilot study (Appendix D) was conducted to investigate which common ballistic exercises acutely induced desired changes in the force-time series relative to the standard CMJ force-time series. The findings from this pilot study indicated that an attenuated (or assisted) CMJ acutely elicited greater CMJ performance, unloading of bodyweight, eccentric peak velocity, braking impulse, downwards displacement and SSC preload and an earlier T_{PF} compared to other CMJ exercise variations. Similar changes in jump strategy and CMJ performance variables during assisted CMJ conditions have been previously reported, which provided confidence in implementing the band-assisted CMJ exercise for the six-week long training intervention (24, 25).

Significant changes in jump strategy were observed for both female and male intervention groups, indicating greater unloading of bodyweight, eccentric peak velocity and braking impulse. However, these adaptions did not result in significant differences in CMJ performance or strength compared to those observed in the control groups. This lack of translation suggests that while the intervention may have enhanced certain components of the eccentric phase of the CMJ, it did not lead to enhanced utilisation of the SSC mechanism. This finding is linked to the non-significant changes in SSC preload or T_{PF}, indicating that the intervention groups did not improve their deceleration capabilities. These findings contrast with previous studies, which reported significant increases ($p < 0.05$; 4.2-7.9%) in jump height as a result of assisted CMJ training (24-26). The differences in findings between investigations may be due to variations in maximal strength or differing exposure to vertical jumping among cohorts (24-26). The current study utilised a single training modality centred around ballistic exercise (assisted and normal CMJs), whereas previous investigations utilised both ballistic exercise and high intensity resistance training modalities, observing significant increases in jump height and changes in jump strategy (18, 19). As maximum strength underpins effective decelerations, it would be suggested that the cohort in the current study may have benefitted from their altered jump strategy if they had possessed (or gained) greater maximal strength.

7.3 Strengths and limitations

A notable strength of the research conducted in this thesis is the sample size and the variety of sporting codes, as most (27, 28) other studies have a relatively smaller sample size. A larger sample size limits the impact of individual outliers prevalent in the data, and omission of outliers still permitted a large enough dataset to offset any possible statistical errors, especially when conducting a stepwise linear regression analysis. Additionally, the sample size allowed for subgroup comparisons within each sex, allowing for a more in-depth analysis of subgroups and providing more nuanced insights. Finally, a large dataset establishes more precise normative values for the CMJ and, more importantly, the isometric squat (ISQ) assessments, as there is very limited normative data on the ISQ in the surrounding literature, especially in female athlete populations.

Another strength of the current study is the robust methodology using gold standard hardware and software to measure the CMJ and ISQ assessments. The use of advanced equipment provided comprehensive data on various metrics, enabling a detailed understanding of an athlete’s performance. Moreover, these tools allow for improved precision and accuracy, allowing for reliable data collection while minimising error measurements. The equipment and software utilised in this study helped establish uniform benchmarks, allowing for fair comparisons to be made across investigations in the future.

The research presented several limitations. First, the study monitored individual athlete performance by averaging the two best CMJ trials of each athlete, where analysing the single best jump could potentially provide a more accurate representation of a jump strategy relative to the performance of that CMJ. However, this approach was chosen in order to improve the reliability of the CMJ assessment.

Second, the limited presence of stronger female athletes may have impacted the representativeness and generalisability of the findings in Chapter 5. Included in this limitation is the lack of surrounding ISQ data regarding female populations to confirm the aforementioned limitation. Lastly, the intervention focused on field hockey players whose strength capacities were lower than those of similar studies, which may have inhibited the extent of CMJ performance improvements observed in Chapter 6.

7.4 Practical implications

The findings from this research offer several practical implications for practitioners involved in monitoring and optimising CMJ performance. As previously mentioned, CMJ performance and concentric-phase variables have consistently shown acceptable variability across investigations. This acceptable variability provides practitioners with confidence to utilise these metrics in both short- and long-term assessments. These variables can be used to effectively track progress, make informed decisions about training interventions, and monitor athletic development over time. However, when interpreting eccentric-phase jump strategy metrics it was cautioned that practitioners should conduct a thorough analysis, due to their unacceptable variability in the current cohort, to avoid potential misinterpretations that could impact training decisions. This caution is particularly important when designing training programmes aimed at improving eccentric-phase jump strategy.

Eccentric-phase jump strategy was found to influence CMJ performance, reinforcing the importance of understanding and optimising these metrics to maximise CMJ outcomes. Each CMJ performance measure was found to have at least one significant correlation with a jump strategy metric: jump height and downwards displacement, take-off momentum and unloading of bodyweight, and RSI_{mod} and SSC preload. The pairing of CMJ performance measures and jump strategy metrics emphasise the need to monitor these metrics when aiming to enhance CMJ performance.

Chapter 5 demonstrated that attaining greater levels of maximal strength is more beneficial than optimising jump strategy when seeking greater CMJ performance. However, the best CMJ performance was achieved by the strong male group, demonstrating the synergy of both maximal strength and optimised jump strategy. The results of the current investigation suggest that prioritising maximal strength development before, or along with, altering jump strategy metrics may be more effective. This approach is particularly important for athletes who may not possess sufficient muscular strength to benefit from changes in jump strategy alone. This was further emphasised in Chapter 6, as the observed changes in jump strategy in the intervention groups did not translate into improved CMJ performance, likely due to the cohort possessing insufficient muscular strength. Practitioners can utilise the assisted CMJ exercise to increase eccentric movement velocities in their athletes, but it is recommended to pair this exercise with high-intensity resistance training to fully harness the benefits of the SSC mechanism.

7.5 Final remarks

This thesis has illuminated the intricate relationship between jump strategy, lower-body physical characteristics, and performance enhancement through a series of investigations and a targeted training intervention. While acknowledging the complexities and variability inherent in CMJ metrics, this research offers practical suggestions for practitioners aiming to optimise jump performance. From caution in interpreting eccentric-phase jump strategy variables to the prioritisation of maximal strength development alongside jump strategy optimisation, the findings underscore the biomechanical nature of performance enhancement with regards to lower-body physical characteristics. This thesis provides a foundation for further exploration and refinement of training methodologies aimed at unlocking the full potential of athletes in the realm of jump performance.

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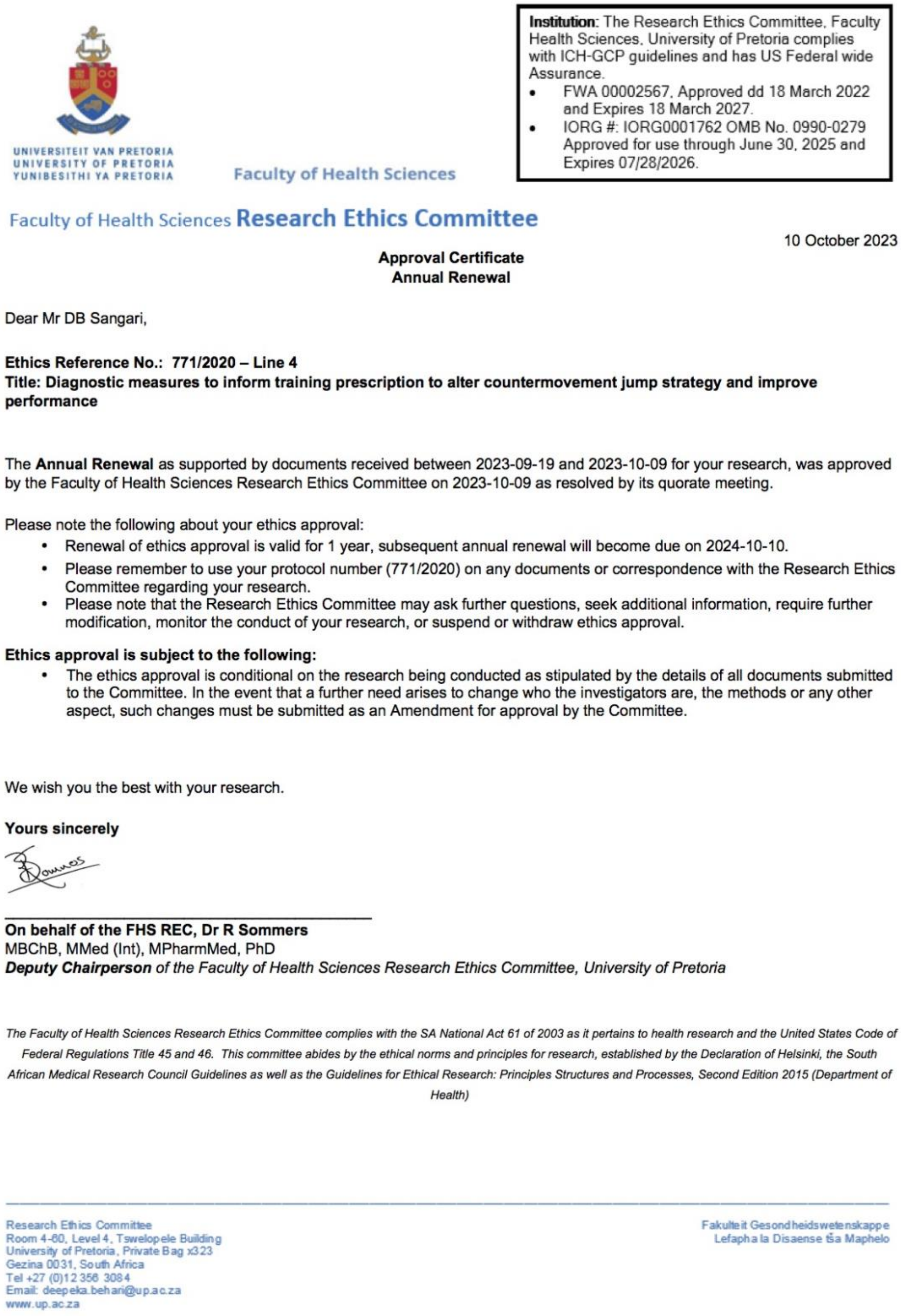
Appendices

Appendix A: Ethical Approval



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Faculty of Health Sciences

Institution: The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.

- FWA 00002567, Approved dd 18 March 2022 and Expires 18 March 2027.
- IORG #: IORG0001762 OMB No. 0990-0279 Approved for use through June 30, 2025 and Expires 07/28/2026.

Faculty of Health Sciences **Research Ethics Committee**

10 October 2023

Approval Certificate
Annual Renewal

Dear Mr DB Sangari,

Ethics Reference No.: 771/2020 – Line 4
Title: Diagnostic measures to inform training prescription to alter countermovement jump strategy and improve performance

The **Annual Renewal** as supported by documents received between 2023-09-19 and 2023-10-09 for your research, was approved by the Faculty of Health Sciences Research Ethics Committee on 2023-10-09 as resolved by its quorate meeting.

Please note the following about your ethics approval:

- Renewal of ethics approval is valid for 1 year, subsequent annual renewal will become due on 2024-10-10.
- Please remember to use your protocol number (771/2020) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, monitor the conduct of your research, or suspend or withdraw ethics approval.

Ethics approval is subject to the following:

- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

On behalf of the FHS REC, Dr R Sommers
MBChB, MMed (Int), MPharmMed, PhD
Deputy Chairperson *of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria*

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes, Second Edition 2015 (Department of Health)

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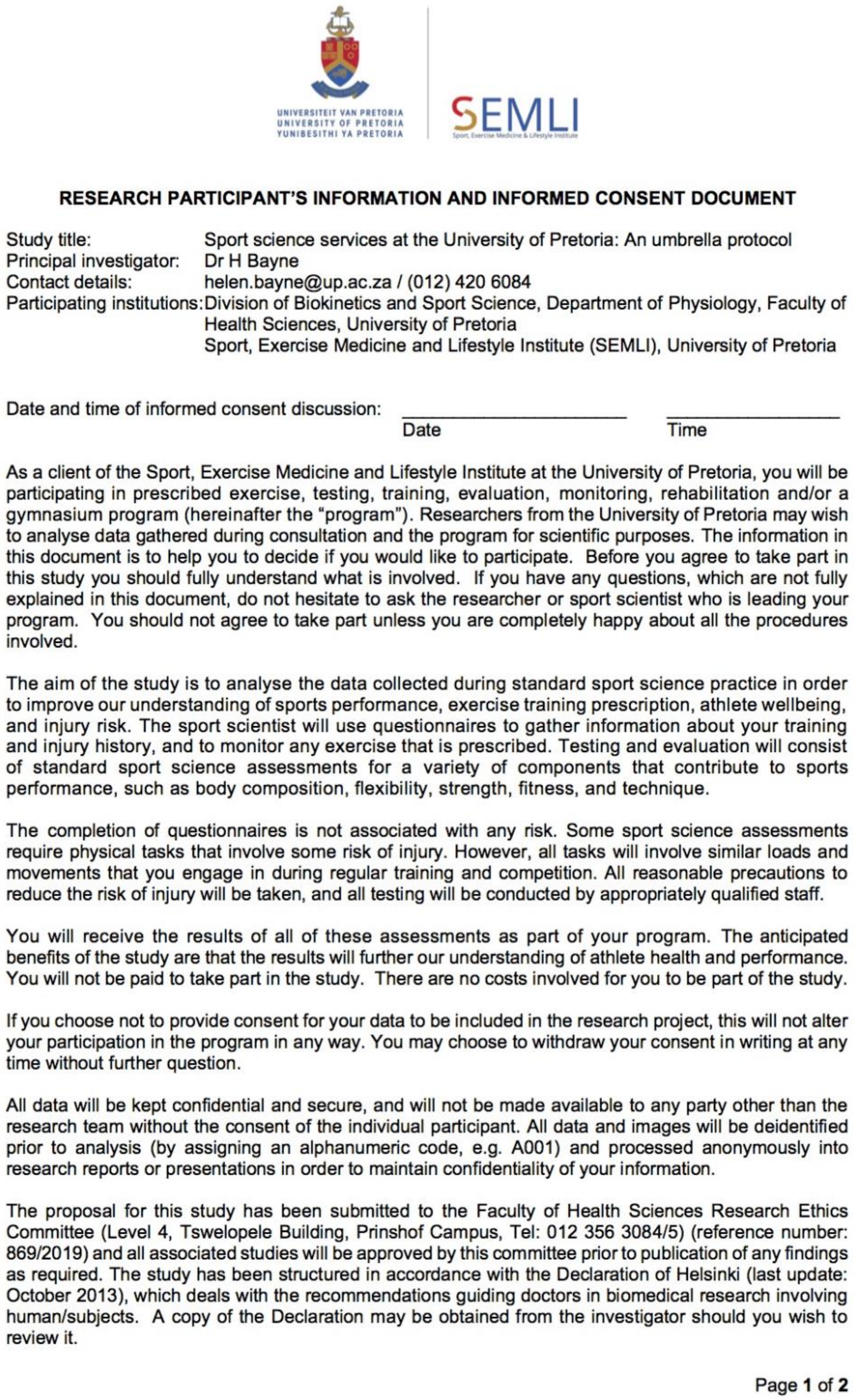
Fakulteit Gesondheidswetenskappe
Lefapha la Disaense tša Maphelo

Appendix B: Informed Consent



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RESEARCH PARTICIPANT'S INFORMATION AND INFORMED CONSENT DOCUMENT

Study title: Sport science services at the University of Pretoria: An umbrella protocol
Principal investigator: Dr H Bayne
Contact details: helen.bayne@up.ac.za / (012) 420 6084
Participating institutions: Division of Biokinetics and Sport Science, Department of Physiology, Faculty of Health Sciences, University of Pretoria
Sport, Exercise Medicine and Lifestyle Institute (SEMLI), University of Pretoria

Date and time of informed consent discussion: ______________________ Date ________________ Time

As a client of the Sport, Exercise Medicine and Lifestyle Institute at the University of Pretoria, you will be participating in prescribed exercise, testing, training, evaluation, monitoring, rehabilitation and/or a gymnasium program (hereinafter the "program"). Researchers from the University of Pretoria may wish to analyse data gathered during consultation and the program for scientific purposes. The information in this document is to help you to decide if you would like to participate. Before you agree to take part in this study you should fully understand what is involved. If you have any questions, which are not fully explained in this document, do not hesitate to ask the researcher or sport scientist who is leading your program. You should not agree to take part unless you are completely happy about all the procedures involved.

The aim of the study is to analyse the data collected during standard sport science practice in order to improve our understanding of sports performance, exercise training prescription, athlete wellbeing, and injury risk. The sport scientist will use questionnaires to gather information about your training and injury history, and to monitor any exercise that is prescribed. Testing and evaluation will consist of standard sport science assessments for a variety of components that contribute to sports performance, such as body composition, flexibility, strength, fitness, and technique.

The completion of questionnaires is not associated with any risk. Some sport science assessments require physical tasks that involve some risk of injury. However, all tasks will involve similar loads and movements that you engage in during regular training and competition. All reasonable precautions to reduce the risk of injury will be taken, and all testing will be conducted by appropriately qualified staff.

You will receive the results of all of these assessments as part of your program. The anticipated benefits of the study are that the results will further our understanding of athlete health and performance. You will not be paid to take part in the study. There are no costs involved for you to be part of the study.

If you choose not to provide consent for your data to be included in the research project, this will not alter your participation in the program in any way. You may choose to withdraw your consent in writing at any time without further question.

All data will be kept confidential and secure, and will not be made available to any party other than the research team without the consent of the individual participant. All data and images will be deidentified prior to analysis (by assigning an alphanumeric code, e.g. A001) and processed anonymously into research reports or presentations in order to maintain confidentiality of your information.

The proposal for this study has been submitted to the Faculty of Health Sciences Research Ethics Committee (Level 4, Tswelopele Building, Prinshof Campus, Tel: 012 356 3084/5) (reference number: 869/2019) and all associated studies will be approved by this committee prior to publication of any findings as required. The study has been structured in accordance with the Declaration of Helsinki (last update: October 2013), which deals with the recommendations guiding doctors in biomedical research involving human/subjects. A copy of the Declaration may be obtained from the investigator should you wish to review it.

Page **1** of **2**

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If you have any questions concerning this study, you should contact the principal investigator using the details provided on page one.

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Consent to participate in this study

- I confirm that the person requesting my consent to take part in this study has told me about the nature and process, any risks or discomforts, and the benefits of the study.
- I have also received, read and understood the above written information about the study.
- I have had adequate time to ask questions and I have no objections to participate in this study.
- I am aware that the information obtained in the study, including personal details, will be anonymously processed and presented in the reporting of results.
- I understand that I will not be penalised in any way should I wish to discontinue with the study and that withdrawal will not affect my further treatments.
- I am participating willingly.
- I have received a signed copy of this informed consent agreement.

____________________________ Participant's name (Please print)	____________________ Date
____________________________ Participant's signature	____________________ Date
____________________________ Researcher's name (Please print)	____________________ Date
____________________________ Researcher's signature	____________________ Date

Page **2** of **2**

Appendix C: Parent/Guardian Consent

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INFORMATION AND INFORMED CONSENT FORM: PARENT/LEGAL GUARDIAN OF A PARTICIPANT AGED 7 – 17 YEARS

Study title: Sport science services at the University of Pretoria: An umbrella protocol
Principal investigator: Dr H Bayne
Contact details: helen.bayne@up.ac.za / (012) 420 6084
Participating institutions: Division of Biokinetics and Sport Science, Department of Physiology, Faculty of Health Sciences, University of Pretoria
Sport, Exercise Medicine and Lifestyle Institute (SEMLI), University of Pretoria

Date and time of informed consent discussion: ______________________ Date ________________ Time

As a client of the Sport, Exercise Medicine and Lifestyle Institute at the University of Pretoria, your child will be participating in prescribed exercise, testing, training, evaluation, monitoring, rehabilitation and/or a gymnasium program (hereinafter the “program”). Researchers from the University of Pretoria may wish to analyse data gathered during consultation and the program for scientific purposes. The information in this document is to help you to decide if you would like your child to participate. Before you agree that your child may take part, you should fully understand what is involved. If you have any questions, which are not fully explained in this document, do not hesitate to ask the researcher or sport scientist who is leading your child’s program. You should not agree to take part unless you are completely happy about all the procedures involved.

The aim of the study is to analyse the data collected during standard sport science practice in order to improve our understanding of sports performance, exercise training prescription, athlete wellbeing, and injury risk. The sport scientist will use questionnaires to gather information about your child’s training and injury history, and to monitor any exercise that is prescribed. Testing and evaluation will consist of standard sport science assessments for a variety of components that contribute to sports performance, such as body composition, flexibility, strength, fitness, and technique.

The completion of questionnaires is not associated with any risk. Some sport science assessments require physical tasks that involve some risk of injury. However, all tasks will involve similar loads and movements that your child engages in during regular training and competition. All reasonable precautions to reduce the risk of injury will be taken, and all testing will be conducted by appropriately qualified staff.

You will receive the results of these assessments as part of the program. The anticipated benefits of the study are that the findings will further our understanding of athlete health and performance. You/your child will not be paid to take part in the study.

If you choose not to provide consent for your child’s data to be included in the research project, this will not alter their participation in the program in any way. You may choose to withdraw your consent in writing at any time without further question.

All data will be kept confidential and secure, and will not be made available to any party other than the research team without the consent of the individual participant. All data and images will be deidentified prior to analysis (by assigning an alphanumeric code, e.g. A001) and processed anonymously into research reports or presentations in order to maintain confidentiality.

The proposal for this study has been submitted to the Faculty of Health Sciences Research Ethics Committee (Level 4, Tswelopele Building, Prinshof Campus, Tel: 012 356 3084/5) (reference number: 869/2019) and all associated studies will be approved by this committee prior to publication of any findings as required. The study has been structured in accordance with the Declaration of Helsinki (last update:

October 2013), which deals with the recommendations guiding doctors in biomedical research involving human/subjects. A copy of the Declaration may be obtained from the investigator should you wish to review it.

If you have any questions concerning this study, you should contact the principal investigator using the details provided on page one.

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Consent to participate in this study

☐ I confirm that the person requesting my consent for my child to take part in this study has told me about the nature and process, any risks or discomforts, and the benefits of the study.
☐ I have also received, read and understood the above written information about the study.
☐ I have had adequate time to ask questions and I have no objections for my child to participate in this study.
☐ I am aware that the information obtained in the study, including personal details, will be anonymously processed and presented in the reporting of results.
☐ I understand that my child will not be penalised in any way should I wish to discontinue with the study and that withdrawal will not affect my further treatments.
☐ My child is participating willingly.
☐ I have received a signed copy of this informed consent agreement.

_______________________________________ Parent / Legal Guardian’s name (Please print)	_______________________ Date
_______________________________________ Parent / Legal Guardian’s signature	_______________________ Date
_______________________________________ Researcher’s name (Please print)	_______________________ Date
_______________________________________ Researcher’s signature	_______________________ Date

Appendix D: A Comparison of Countermovement Jump Variations and their Influence on Jump Strategy: A Pilot Study

8.1 Introduction

Ballistic and plyometric exercises are commonly implemented in training programmes to increase lower-body power and the changes in jump performance are commonly assessed through the countermovement jump (CMJ) test (1). Plyometric exercises or movements are completed in a shorter time (typically < 250ms) than ballistic exercises (>250 ms), yet both are used to improve reactive strength, which is the ability to rapidly transition from eccentric to concentric muscle actions (2). The coupling of eccentric and concentric muscle actions is often referred to as the stretch-shorten cycle (SSC). The eccentric component of the SSC allows for additional generation of ground reaction force (GRF) prior to the initiation of the concentric phase (SSC preload), thereby enhancing concentric impulse and, ultimately, performance more than concentric-only exercises do (3). The manner in which an athlete moves their COM through the eccentric phase (velocity and amplitude) is referred to as jump strategy and has a direct influence on SSC preload and an indirect influence on concentric performance (4, 5). Many plyometric and ballistic exercises have been reported to improve jump performance; however, there is limited information regarding their influence on jump strategy.

Few variations of the CMJ exercise have been investigated for their direct influence on jump strategy. Band assisted (BA) CMJs have been used to elicit supramaximal (or overspeed) training effects on the user, where greater unloading of bodyweight (BW) and increased concentric peak velocity have been observed; however, lower SSC preloads were also reported (6). In contrast, band resisted (BR) CMJs elicit an increase in load and have been observed to have less unloading of BW but a greater change in unloading of BW compared to BA jumps (6). Additionally, it has been reported that BR jumps had greater SSC preload compared to BA jumps and regular CMJs; however, it was suggested that there is a trade-off between force and velocity, as concentric peak velocity was lower in BR jumps than in BA and CMJs (6). This finding may have been due to the inclusion of band attachments throughout both eccentric and concentric phases, where studies examining accentuated eccentrically loaded (AEL) jumps have reported contrasting results. Sheppard (7) and Aboodarda (8) implemented AEL dumbbell (DB) and BR jump protocols respectively and observed similar findings of increases in concentric peak power, force, velocity and vertical jump height. Although the aforementioned CMJ variations have previously been investigated, inconsistent information was reported regarding jump strategy variables (specifically eccentric variables such as acceleration, velocity, displacement and GRF) across studies, thus limiting the inferences that can be made regarding these CMJ variations.

Although these variations of the CMJ have been investigated for their influence on jump strategy, direct comparisons between these aforementioned exercises have not been conducted. The aim of this study was to determine which CMJ variations promoted a more optimised jump strategy, characterised by a greater unloading of BW, eccentric peak velocity, SSC preload and a peak GRF that coincides with amortisation.

8.2 Materials and methods

8.2.1 Participants

A total of 10 recreationally active participants (age = 24 ± 3.8 yr, weight = 69.3 ± 9.3 kg, height = 1.70 ± 0.05 m) volunteered and provided written informed consent to participate in this study. All participants were over the age of 18 and did not require parental consent to participate in this study. Ethical approval was granted by Faculty of Health Sciences Research Ethics Committee (771/2020).

8.2.2 Procedures

Every participant completed a standardised warm up, including three sub-maximal CMJs with increasing intensity for each jump. Participants were asked to stand on the dual force platform (JM6090-06, Bertec, USA) with one foot on each plate. Participants stood still prior to initiating the first CMJ to allow determination of bodyweight (BW) for post-testing analysis and then performed three CMJs with 30 seconds of rest between each jump, with their arms akimbo to eliminate the use of arm swing.

Participants performed band assisted and resisted jumps on the force platform, surrounded by a custom-built squat rack fitted on either side of the force plates. The elastic bands were attached to the top of the squat rack for the assisted jumps and the bottom of the rack for resisted jumps. The other end of each band was held in the participant's hand while standing akimbo. The tension of the assisted band was set to reduce the participants BW by 20% and the resisted band was set to add 20% of BW. For the DB AEL jumps, a weight of 20 kg (10 kg per hand) was selected based off of a previous investigation that stated that this specific weight would evoke the greatest improvement in kinetic and kinematic measures (7). Participants were instructed to hold the DBs with straight arms and to release the DBs immediately prior to the moment of concentric initiation. Participants were instructed to "jump as high as possible, as fast as possible" and "maintain full extension during the flight phase until the moment of touchdown" and countermovement depth was not controlled. A trial was repeated if the participant removed their hand/s from their hips when performing a CMJ (excluding the DB AEL trials), did not land on the platform with both feet and/or tucked their legs during the jump or upon landing. Participants performed three jumps, whereafter data from the two trials with the greatest jump heights were averaged.

8.2.3 Data collection and analysis

Ground reaction force data was sampled at 1000 Hz and recorded using ForceDecks software (VALD Performance, Australia). Force and time data were recorded for each jump trial and variables of interest were calculated from the force-time record. Jump height was calculated using COM take-off velocity, which was determined through the impulse-momentum method (9). The data were exported to Microsoft Excel (version 16.16.27) for data cleaning. Other metrics used to measure jump performance included the modified reactive strength index (RSI_{mod}) calculated as jump height divided by the time take to complete the CMJ and take-off momentum (TO_p) calculated as the product of BW and take-off velocity.

CMJ phases were defined by previously established criteria (10, 11). The first CMJ phase was the weighing phase, where the participant was asked to stand completely still on the force platforms for at least one second to record body weight (BW) and eliminate signal noise prior to initiating the CMJ (11). The eccentric phase was divided into two distinct phases: the unweighting and braking phases. The initiation of the unweighting phase was identified when the vertical force decreased by a threshold of 20 N less than the participant's body weight. The braking phase began from the moment after peak negative velocity to the moment negative COM velocity equalled zero (which coincided with the lowest depth of the countermovement). The propulsion phase began when the participant's upwards COM vertical velocity increased above a threshold of 0.01 $m.s^{-1}$ (11) and ended when the participant was no longer in contact with the force platform and had entered the flight phase of the CMJ, based on a threshold of 30 N. Downwards displacement (D_{ecc}), eccentric peak velocity (V_{ecc}) and minimum eccentric force (F_{min}) values were considered negative. All force metrics – including F_{min}, force at zero velocity (F_{0V}) and braking impulse ($I_{braking}$) – were reported as net force values (GRF – BW) and normalised to body mass ($N.kg^{-1}$). The metric $I_{braking}$ was calculated as the area under the force-time graph between V_{ecc} and initiation of the concentric phase. The timing of peak force (T_{PF}) was included as a metric to determine how effective an athlete is at utilising the SSC mechanism, was calculated as the time from F_{0V} to peak vertical GRF, and expressed as a percentage of the concentric-phase duration. Time to take-off (TTT) was included in the descriptive statistics as it is a component required for the calculation of the RSI_{mod}.

8.2.4 Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics (Version 27) for Windows. The interquartile rule was used to identify and remove outliers, which included observations lower than the first quartile minus 1.5 times the interquartile range or those above the third quartile plus 1.5 times the interquartile rule. Data were presented as means and standard deviations to represent centrality and spread of data. Normality was assessed using the Shapiro-Wilk test with an alpha level set at 0.05, where a p value greater than 0.05 indicated that the data were normally distributed. An analysis of variance (ANOVA) was conducted to examine the influences of each jumping condition on jump performance and strategy variables. For statistically significant findings, a post hoc (Bonferroni) test and an independent T-test were conducted to determine the magnitude of the differences between conditions. Effect size (Cohen's d) was used to determine the magnitude of the differences between and the strength of the values were selected based on the standards used by previous investigations (12, 13) and interpreted as trivial (≤0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (2.0–4.0) (14). The statistical significance threshold was set a priori at $\alpha = 0.05$ for both the ANOVA, post hoc and independent T-test.

8.3 Results

The means and standard deviations for each variable of interest within each jump condition are presented in Table 8.1.

8.3.1 Jump performance

A significant interaction for jump height ($p = 0.002$) between CMJ conditions was observed. A post hoc revealed that the BA ($p = 0.004$; ES = 0.21), CMJ ($p = 0.041$; ES = 0.16) and DB AEL ($p = 0.01$; ES = 0.19) were greater than the BR condition by a trivial to small effect. Significant differences were observed between conditions for RSI_{mod} ($p = 0.002$), as BA ($p = 0.002$; ES = 0.02) and DB AEL ($p = 0.023$; ES = 0.02) were greater than the BR condition by trivial effects. Finally, significant differences in TO_p ($p = 0.018$) were reported, as both BA ($p = 0.048$; ES = 0.31) and DB AEL ($p = 0.02$; ES = 0.33) were greater than the BR condition by a small effect.

8.3.2 Jump strategy

Significant differences were observed for all jump strategy variables between jump conditions, with the exception of TTT. The BA condition was observed to have a lower F_{min} ($p = 0.002$; ES = 0.08) than DB AEL and a greater F_{0V} than the BR condition ($p = 0.01$; ES = 0.11). Significant differences in V_{ecc} were observed, as the BA condition was significantly lower than CMJ ($p = 0.008$; ES = 0.03), BR ($p = 0.017$; ES = 0.03) and DB AEL ($p = 0.001$; ES = 0.06), while CMJ ($p = 0.025$; ES = 0.03) and the BR condition (p = 0.009; ES = 0.03) was significantly lower than DB AEL. The BA jumps produced a lower D_{ecc} (p = 0.003; ES = 0.24) than DB AEL jumps.

Significant differences in $I_{braking}$ were observed, as BA (p = 0.02; ES = 0.27) and BR (p = 0.025; ES = 0.26) were greater than DB AEL by a small effect. The T_{PF} in the assisted (p = 0.033; ES = 0.18), CMJ (p = 0.047; ES = 0.17) and resisted (p = 0.002; ES = 0.2) conditions occurred earlier than the DBAEL condition by trivial to small effects respectively.

Table 8.1 Comparison of jump performance and jump strategy variables for each jumping condition

	CMJ			BA			BR			DB AEL		
Jump performance variables	Mean	SD		Mean	SD		Mean	SD		Mean	SD	
Jump height (cm)	35.0	± 12.3	§	39.0	± 11.4	§	19.8	± 9.3		38.3	± 12.8	§
RSI_{mod} (AU)	0.45	± 0.17		0.52	± 0.15	§	0.25	± 0.12		0.47	± 0.17	§
TO_p (kg.m.s^{-1})	182	± 46		192	± 43	§	137	± 52		190	± 59	§
Jump strategy variables												
F_{min} (N.kg^{-1})	-7.69	± 1.15		-8.70	± 0.77	‡	-7.41	± 1.46		-6.19	± 1.96	
V_{ecc} (m.s^{-1})	-1.42	± 0.24	§‡	-1.81	± 0.28	*§‡	-1.39	± 0.31		-1.01	± 0.34	§
$I_{braking}$ (N.s)	1.42	± 0.24		1.81	± 0.28	‡	1.39	± 0.31	‡	1.01	± 0.34	
D_{ecc} (cm)	-38.0	± 10.1		-48.4	± 17.0	‡	-39.4	± 11.8		-24.2	± 9.0	
F_{0V} (N.kg^{-1})	14.9	± 2.9		16.7	± 3.2	§	11.2	± 3.2		12.6	± 5.1	
T_{PF} (%)	1.7	± 9.5		-0.6	± 17.0	‡	-6.8	± 12.8	‡	17.3	± 11.5	
Additional variables												
TTT (ms)	802	± 132		770	± 143		813	± 116		821	± 96	

* = Significantly different from CMJ; # = significantly different from assisted; § significantly different from resisted; ‡ = significantly different from DB AEL

8.4 Discussion

The aim of this study was to determine which of the selected CMJ variations prompted a more optimised jump strategy. The results of this investigation indicated that 1) the BA and DB AEL conditions elicited superior CMJ performances than the CMJ and BR conditions did, and 2) the BA jump condition produced the most optimised jump strategy of the jump conditions.

The current investigation observed the BA and DB AEL conditions to have significantly greater jump height, RSI_{mod} and TO_p than the BR condition. Previous researchers have reported that BA and AEL jumps produce significantly ($p < 0.05$) superior jump performances relative to the CMJ; however, this was not observed in the current investigation (7, 8). Assistance training in both jumping and sprinting elicits overspeed training effects (allowing muscles to contract faster than without the assistance), thereby increasing concentric peak and take-off velocity and increasing jump height in the case of the BA jump. The BR jumps have produced the lowest jump heights across investigations (relative to BA jumps and the CMJ), likely due to the additional loading throughout the concentric phase restricting the contractile velocity of the agonist muscles (6, 15). Although the BA and DB AEL jumps were not significantly different from the CMJ, they produced a practically relevant increase (9-11%) in jump height and should be considered for prescription in an intervention protocol.

The BA jumps produced the most optimal jump strategy (compared to BR and DB AEL jumps), characterised by greater unloading of BW (F_{min}), V_{ecc}, $I_{braking}$, F_{0V}, D_{ecc} and a T_{PF} coinciding closest to amortisation. Argus et al. (6) reported similar findings, as they observed lower F_{min} during the assisted jumps; however, decreases in F_{0V} during BA jumps (10%) and increases in F_{0V} during resisted jumps (5%) were also reported, contrasting the findings of the current study. The BA jump demonstrated significantly lower V_{ecc} than all other jump conditions did, while DB AEL presented the highest V_{ecc}. The latter observation contradicts the findings of Aboodarda et al. (8), which reported lower V_{ecc} when comparing BR AEL (with 30% of added BW) to normal CMJs (33%; $p < 0.05$); however, the V_{ecc} values reported in their study were relatively smaller ($0.18 – 0.24\ m.s^{-1}$) than those reported in both the current research and in previous studies (16-18). This may suggest that the subjects lowered themselves extremely slowly or that an incorrect methodology was used to calculate kinematic variables (such as the differences between relative net concentric impulse and concentric peak velocity reported in their investigation) (8). Finally, D_{ecc} was lowest in the BA jumps but only significantly different to DB AEL jumps, which aligns with the findings Aboodarda et al. (8), who reported increases in D_{ecc} values between BR AEL jumps and CMJs (13%; $p < 0.05$). Additionally, Markovic et al. (15) observed lower D_{ecc} for both BA (28-49%) and BR (37-42%) conditions when compared to the CMJ. The jump strategy metrics

V_{ecc} and D_{ecc} are suggested to be major influences on the SSC, as the velocity (V_{ecc}) and amplitude (D_{ecc}) during eccentric movement can directly influence SSC preload.

8.5 Conclusion

The results of this investigation and observations from previous investigations suggest that the BA and DB AEL jumps are most likely to induce superior jump performance in jump height, RSI_{mod} and TO_p than resisted jumps are if implemented in a long-term training intervention. Analysis of the influences that each jump condition elicited on jump strategy revealed that the BA jump produced the most desirable jump strategy, as it induced a greater unloading of BW, downwards displacement, velocity of the COM, SSC preload, and an optimised T_{PF}. As assisted exercises have been previously observed to successfully improve jumping and sprinting performance, prescribing BA jumps to athletes as a method of inducing changes in jump strategy and improvements in CMJ performance should be considered by strength and conditioning practitioners.

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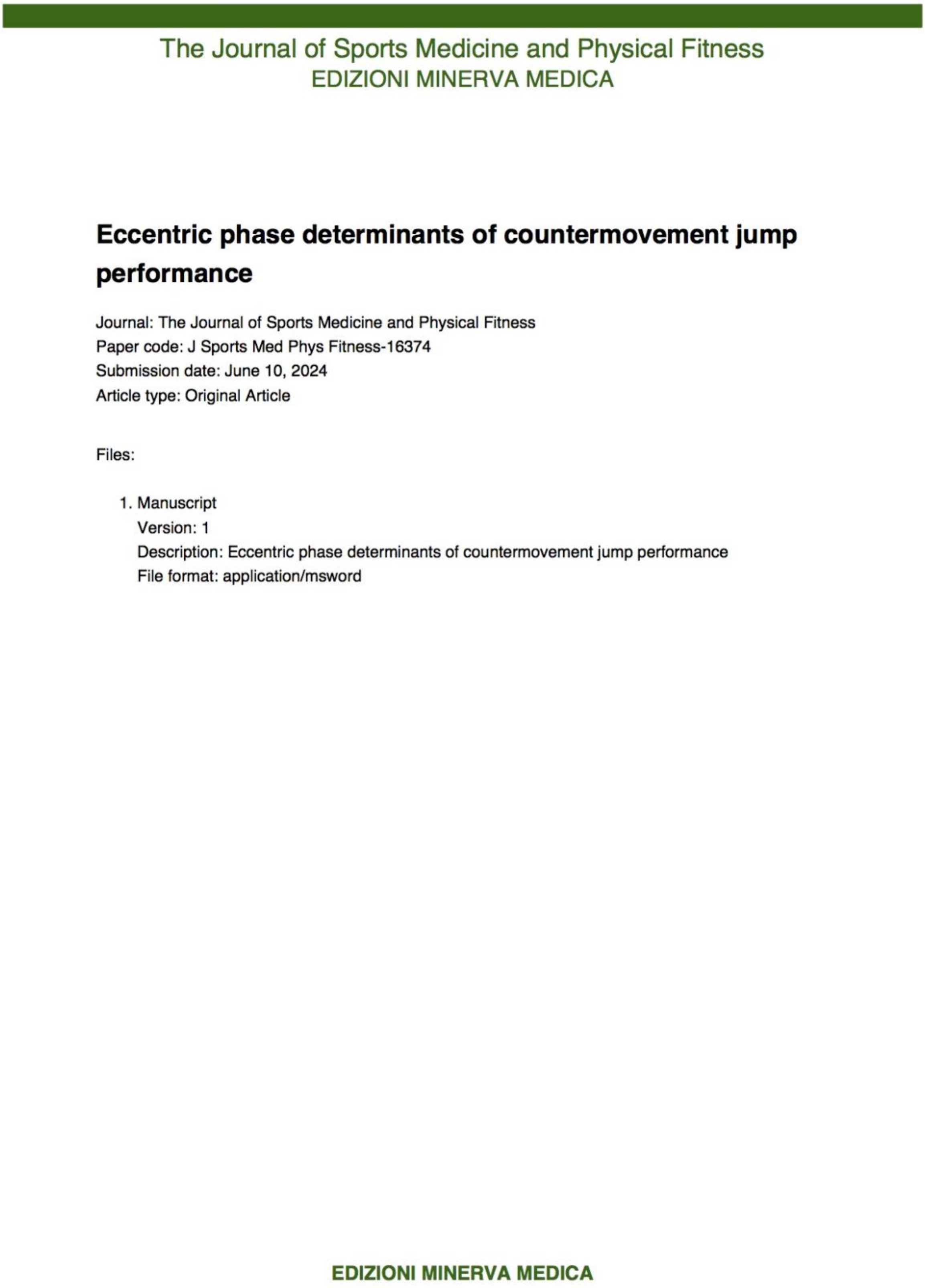
Appendix E: Chapter 4 Proof of Journal Submission



The Journal of Sports Medicine and Physical Fitness
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Eccentric phase determinants of countermovement jump performance

Journal: The Journal of Sports Medicine and Physical Fitness
Paper code: J Sports Med Phys Fitness-16374
Submission date: June 10, 2024
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Files:

1. Manuscript
   Version: 1
   Description: Eccentric phase determinants of countermovement jump performance
   File format: application/msword

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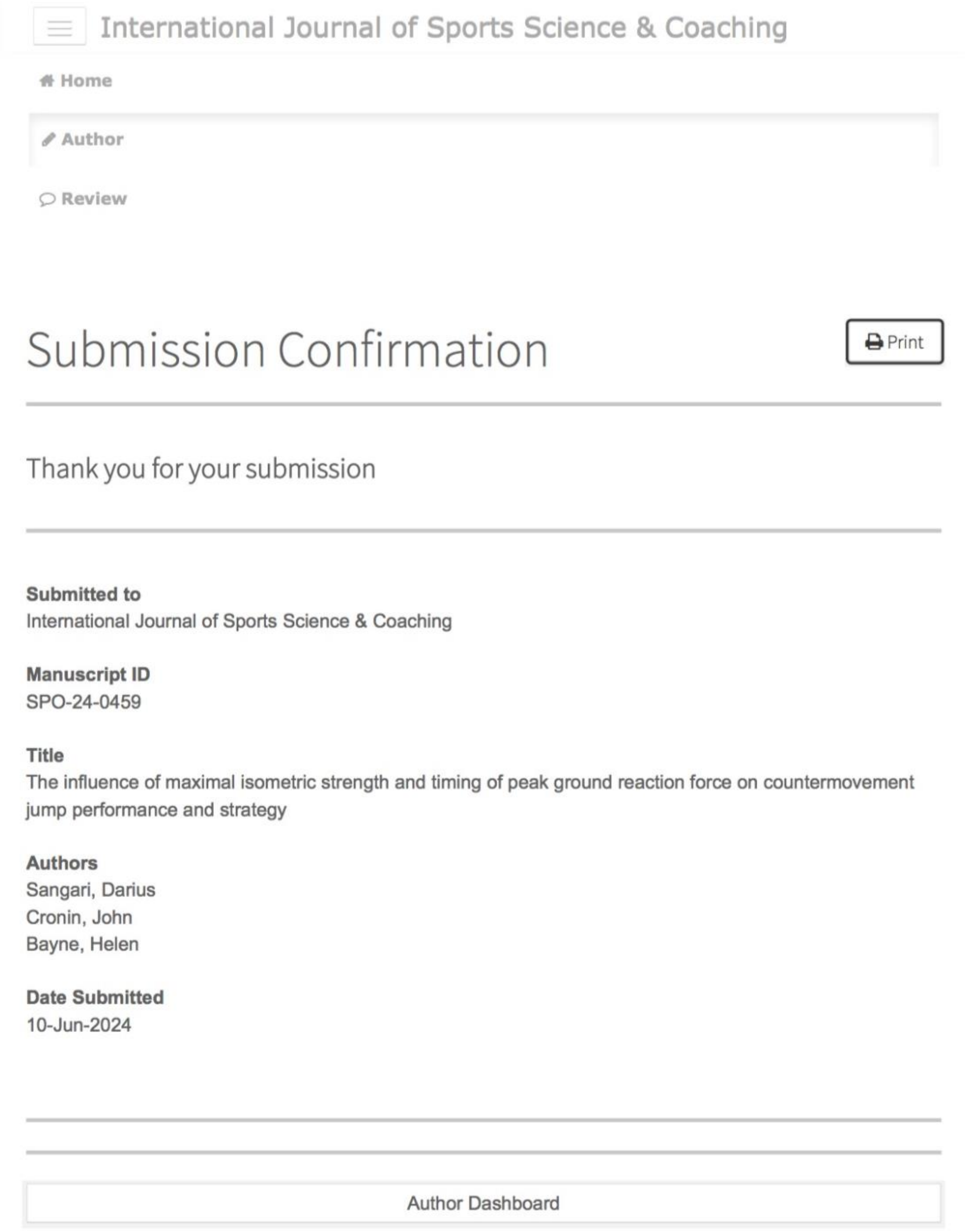
Appendix F: Chapter 5 Proof of Journal Submission



Submission Confirmation

Thank you for your submission

Submitted to
International Journal of Sports Science & Coaching

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Title
The influence of maximal isometric strength and timing of peak ground reaction force on countermovement jump performance and strategy

Authors
Sangari, Darius
Cronin, John
Bayne, Helen

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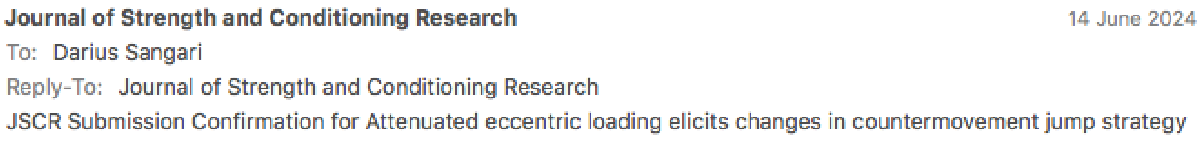
10-Jun-2024

Appendix G: Chapter 6 Proof of Journal Submission

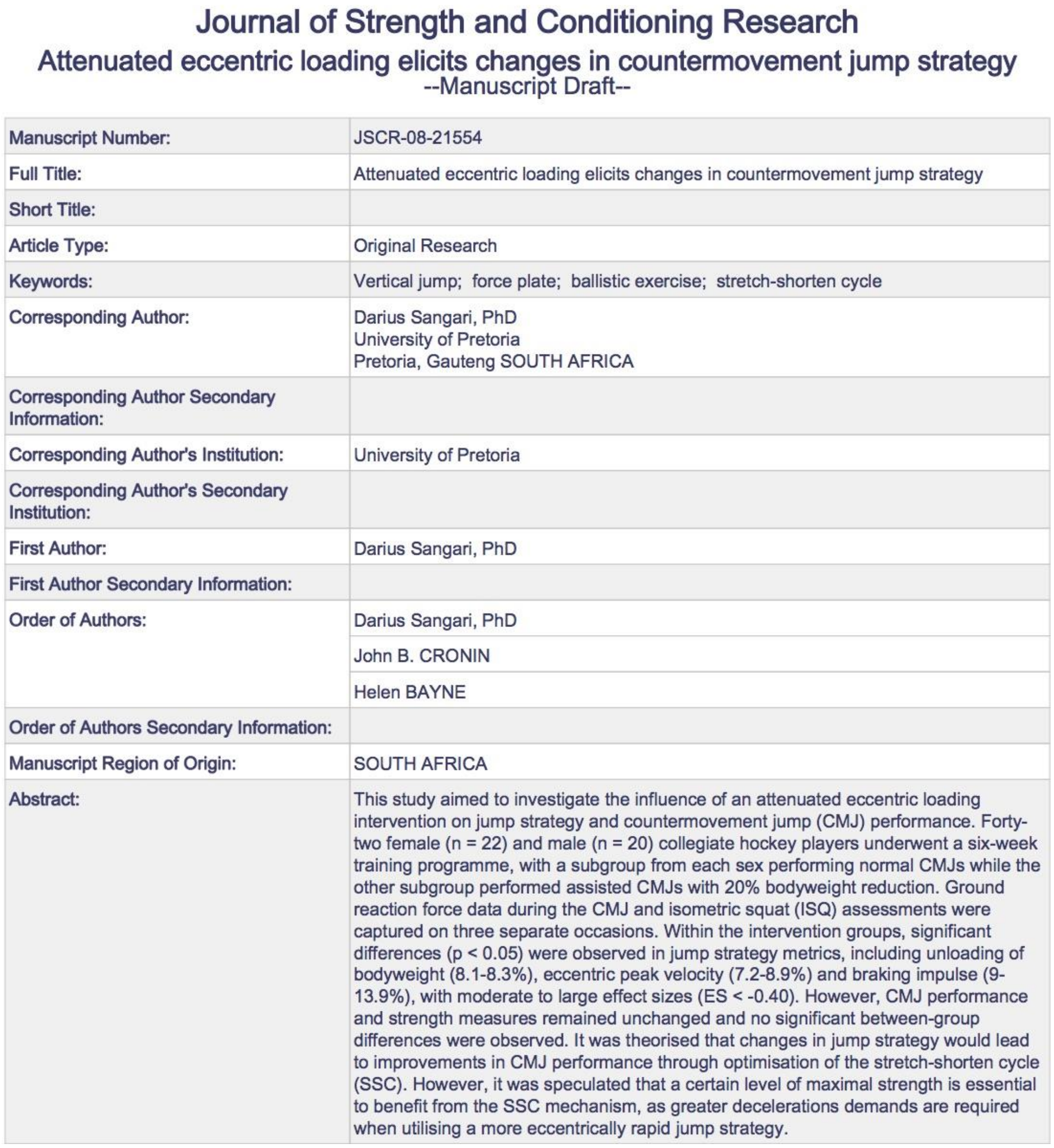


Journal of Strength and Conditioning Research 14 June 2024

To: Darius Sangari

Reply-To: Journal of Strength and Conditioning Research

JSCR Submission Confirmation for Attenuated eccentric loading elicits changes in countermovement jump strategy



Journal of Strength and Conditioning Research

Attenuated eccentric loading elicits changes in countermovement jump strategy

--Manuscript Draft--

Manuscript Number:	JSCR-08-21554
Full Title:	Attenuated eccentric loading elicits changes in countermovement jump strategy
Short Title:	
Article Type:	Original Research
Keywords:	Vertical jump; force plate; ballistic exercise; stretch-shorten cycle
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Abstract:	This study aimed to investigate the influence of an attenuated eccentric loading intervention on jump strategy and countermovement jump (CMJ) performance. Forty-two female (n = 22) and male (n = 20) collegiate hockey players underwent a six-week training programme, with a subgroup from each sex performing normal CMJs while the other subgroup performed assisted CMJs with 20% bodyweight reduction. Ground reaction force data during the CMJ and isometric squat (ISQ) assessments were captured on three separate occasions. Within the intervention groups, significant differences ($p < 0.05$) were observed in jump strategy metrics, including unloading of bodyweight (8.1-8.3%), eccentric peak velocity (7.2-8.9%) and braking impulse (9-13.9%), with moderate to large effect sizes (ES < -0.40). However, CMJ performance and strength measures remained unchanged and no significant between-group differences were observed. It was theorised that changes in jump strategy would lead to improvements in CMJ performance through optimisation of the stretch-shorten cycle (SSC). However, it was speculated that a certain level of maximal strength is essential to benefit from the SSC mechanism, as greater decelerations demands are required when utilising a more eccentrically rapid jump strategy.