The Role of Eccentric Muscle Function and Training in Athletic Performance

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Abstract

Eccentric muscle function is thought to play an important role in human movement. In particular, eccentric muscle function may be especially relevant to the execution of high force fast stretch-shortening cycle (SSC) tasks within athletic performance (e.g. the ability to tolerate large external forces and regulate leg spring stiffness during jumping and sprinting). Although chronic eccentric training has been demonstrated to induce greater increases in SSC performance and leg spring stiffness compared with other training modalities, there have been no studies demonstrating a link between eccentric muscle function *per se* (i.e. maximum eccentric strength and eccentric muscle function under fast SSC conditions) and the performance of high force locomotive tasks such as jumping and sprinting in trained athletes. Furthermore, few studies investigating the effects of chronic eccentric training on athletic performance have recruited resistance trained athletes undertaking an ecologically valid physical preparation program. The overall purpose of this thesis was to elucidate the role of eccentric muscle function and training in athletic performance. In addition to addressing the gaps in the literature with scientific rigour, this research was intended to directly influence the practice of strength and conditioning coaches working within athletic performance. It remains difficult to assess eccentric muscle function during functional multi-articular movement in a practical environment with trained athletes. Therefore, two novel assessment protocols were investigated. Firstly, an assessment of maximum lower body isoinertial eccentric strength was demonstrated to successfully identify an eccentric back squat one repetition maximum (1RM). Furthermore, it was found that the eccentric back squat 1RM was 28 ± 8 % higher than the concentric back squat 1RM in resistance trained participants ($n = 10$). Secondly, eccentric muscle-tendon unit (MTU) function under fast SSC conditions was inferred from braking phase kinetic variables during a drop jump (DJ) in sprint trained participants ($n = 13$). Both novel assessment protocols exhibited acceptable reliability.

The role of eccentric muscle function in athletic performance was then investigated in two cross-sectional studies. The first cross-sectional study investigated how eccentric muscle function contributed to reactive strength in highly trained sprinters ($n = 12$) in comparison to a non-sprint trained control group ($n = 12$). Trained sprinters exhibited a higher DJ reactive strength index (RSI; Effect Size [ES] ±90% confidence limits

[CL]: 3.11 ±0.86) attained primarily by a briefer contact time (ES: -1.49 ±0.53). Very large differences in mean braking force (ES: 2.57 ±0.73) were observed between groups which was closely associated with contact time ($r = -0.93$). Higher levels of reactive strength exhibited by trained sprint athletes may therefore be underpinned by a shorter and more forceful eccentric muscle action. The second cross sectional study investigated the role of isoinertial eccentric strength and eccentric muscle function under fast SSC conditions (i.e. during a DJ) in modelled stiffness regulation during maximum velocity sprinting in highly trained sprinters ($n = 11$) in comparison to trained team sport athletes ($n = 13$). Trained sprinters attained a higher maximum sprinting velocity (ES: 1.54 ±0.85), briefer ground contact time (ES: -1.39 ±0.80) and higher modelled vertical stiffness (ES: 1.74 ±0.96) in comparison with team sport athletes. Trained sprinters also exhibited a moderately higher RSI (ES: 0.71 ±0.74) via the attainment of a briefer and more forceful ground contact phase, while only a possible small difference in isoinertial eccentric force (ES: 0.38 ±0.56) was found between the two groups. RSI demonstrated large to very large associations with maximum velocity ($r = 0.72$) and vertical stiffness ($r = 0.67$), whereas isoinertial eccentric force exhibited weaker correlations with maximum velocity ($r = 0.56$) and vertical stiffness ($r = 0.41$). The stronger association between modelled stiffness regulation at maximum velocity and eccentric muscle function under fast SSC conditions (i.e. DJ mean braking force) compared with maximum isoinertial eccentric strength indicates that the regulation of lower body stiffness may be a somewhat task-specific motor strategy. Therefore, the cross-sectional investigations identified that eccentric muscle function contributes to reactive strength and maximum velocity sprinting capabilities in highly trained athletes.

The final investigation determined the effects of a lower body resistance training program incorporating accentuated eccentric loading (AEL) in comparison with a traditional (TRAD) resistance training program in resistance trained team sport (i.e. Rugby Union) athletes ($n = 14$) undertaking a broader physical preparation program. Two four-week phases of distinct eccentric phase tempos were completed (i.e. slow and fast tempo). Strength, power, speed and muscle properties were assessed at baseline and following each training phase. The slow AEL protocol elicited superior improvements in back squat strength (ES: 0.48 ±0.34), 40m sprint performance (ES: -0.28 ±0.27), maximum sprinting velocity (ES: 0.52 ±0.34) and vertical stiffness at

maximum velocity (ES: 1.12 ±0.72) versus slow TRAD training. In contrast, the second four-week block of fast AEL training elicited a small increase in reactive strength (i.e. RSI via a moderate reduction in contact time), but impaired 40m speed and maximum sprinting velocity. In addition, fast AEL was less effective in improving lower body power (ES: -0.40 ±0.39) versus fast TRAD. This study demonstrated that four weeks of AEL training with a slow eccentric tempo can induce superior improvements in lower body strength, maximum velocity sprinting speed and stiffness regulation in resistance trained athletes in an ecologically valid setting. However, a subsequent four-week phase of AEL training emphasizing a fast eccentric tempo did not lead to additional improvements in strength and may have impaired maximum velocity sprinting capabilities. It was proposed that the second phase of eccentric training could have exceeded the recovery capabilities of the athletes undertaking a concurrent program.

In summary, this thesis identified that eccentric muscle function contributes to high force fast SSC function and therefore athletic performance. However, the regulation of eccentric force under task specific conditions may be more important than maximum eccentric strength. Eccentric training can induce superior improvements (i.e. in comparison to TRAD training) in strength and speed in trained team sport athletes undertaking a concurrent training program, however, it should be incorporated judiciously.

Attestation of Authorship

"I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning."

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List of Co-Authored Publications

Douglas J, Pearson, S, Ross, A, McGuigan M. Eccentric exercise: physiological characteristics and acute responses. Sports Medicine. 2017;47(4):663-675.

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Conference Presentations

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List of Common Abbreviations

1RM	One Repetition Maximum
AEL	Accentuated Eccentric Loading
CI	Confidence Interval
CONC	Concentric Resistance Training
CL	Confidence Limits
CSA	Cross Sectional Area
CV	Coefficient of Variation
DOMS	Delayed Onset Muscle Soreness
DJ	Drop Jump
ECC	Eccentric Resistance Training
EIMD	Exercise Induced Muscle Damage
EMG	Electromyography
ES	Effect Size
ICC	Intra-class Correlation Coefficient
IL	Inertial Load Cycle Ergometer
IRV	Intensity Relative Volume
LPT	Linear Position Transducer
MHC	Myosin Heavy Chain
MTU	Muscle-Tendon Unit
MVC	Maximum Voluntary Contraction
RFD	Rate of Force Development
RSI	Reactive Strength Index
SD	Standard Deviation
SSC	Stretch-Shortening Cycle
SWC	Smallest Worthwhile Change
TEM	Typical Error of Measurement
TRAD	Traditional Resistance Training
VL	Vastus Lateralis

Chapter 1

Introduction

1.1 Background

An eccentric muscle contraction refers to a muscle activity that occurs when the force applied to the muscle exceeds the momentary force produced by the muscle itself, resulting in a lengthening contraction [1]. During human movement, and specifically in gait and jumping movements, the muscle-tendon unit (MTU) generally operates eccentrically as a shock absorber of the gravitational forces exerted upon the body. Energy under such conditions may be absorbed within the MTU and subsequently dissipated as heat (e.g. downhill walking) [2], or alternatively, absorbed and stored as elastic recoil potential energy, a portion of which can be returned during subsequent MTU shortening within the stretch shortening cycle (SSC) [3]. Effective SSC function is thought to be determined by three fundamental conditions; a well-timed pre-activation of muscle(s) preceding the eccentric phase, a short and fast eccentric phase, and an immediate transition between eccentric and concentric phases [4]. The functional significance of the SSC is the amplification of concentric force output (i.e. via elastic strain energy return and short latency stretch reflex potentiation) [2, 4, 5], which is considered critical to the performance of high force locomotive tasks such as the ground contact phase of sprinting where the time available to produce is limited (e.g. ~0.10 s) [1, 6, 7]. It should be acknowledged that it has been debated whether muscle fascicles operate eccentrically or isometrically (i.e. versus tendon and global MTU lengthening) during low force SSC tasks (e.g. countermovement jumping, walking and running) [8-10]. Nonetheless, experimental evidence indicates that a short range eccentric muscle contraction of agonist musculature (e.g. vastus lateralis, gastrocnemius and soleus) can occur during fast and high force lower limb SSC tasks (e.g. drop jumping and high speed running) [9, 11-13]. It is possible that a fast and forceful eccentric contraction aids in the attainment of stiffer quasi-isometric fascicle behaviour which yields less when exposed to high stretch-loads, and therefore, a more effective absorption of braking forces and utilization of elastic elements [11].

It is challenging to assess SSC function under rapid and high force conditions *in vivo* [14, 15], particularly within practical settings. Therefore, it is generally inferred from measures of reactive strength [16]. Reactive strength refers to the ability to rapidly absorb large eccentric (i.e. braking) forces and subsequently return large concentric (i.e. propulsive) forces [17], and is most commonly determined via the reactive

strength index (RSI; flight time [or jump height] divided by contact time) obtained from drop jumping or hopping tasks [16]. Sprinting is a complex motor task influenced by a host of biomechanical and physiological variables [18, 19], however, from a mechanical perspective, faster sprinters apply larger ground reaction forces during a briefer ground contact phase [20-22]. Therefore, reactive strength (i.e. fast SSC function) likely plays a prominent role in the attainment of large ground reaction forces and a high power output in a brief ground contact time [1, 6, 18]. Eccentric muscle function (i.e. a brief and forceful eccentric contraction) contributes to reactive strength during sprinting via enhanced stiffness regulation of the lower limb (i.e. the resistance of the leg to deformation when exposed to a given external force [23]) during the braking phase of ground contact [24], a greater storage and return of elastic energy within the MTU [6, 25], short latency stretch reflex potentiation [14], and subsequently, the amplification of concentric force production during the propulsive phase of ground contact [5, 14]. Therefore, it is possible that enhancements in maximal eccentric strength and eccentric muscle function under SSC conditions will aid in the ability to rapidly absorb large braking forces and subsequently return large propulsive forces during high force locomotive tasks such as sprinting [1, 23].

While eccentric muscle function is integral to human movement, the molecular mechanisms underpinning eccentric contractions remain incompletely understood, especially in comparison to isometric and concentric contractions [26]. There are several phenomena consistently observed during lengthening contractions that remain unexplained by traditional theories of muscle contraction (e.g. [27, 28]); including a greater tension generating capacity [29], residual force enhancement (i.e. an increase in maximal steady state isometric force immediately following muscle lengthening) [30], and a lower metabolic cost (i.e. ATP consumption) per unit of external work [31]. Contemporary models have substantial explanatory promise [32, 33], and it appears that the structural protein titin plays an important contractile role alongside actin and myosin during eccentric contractions [34]. Accordingly, the neural strategies of eccentric contractions also differ in comparison to other contraction types [35, 36]. Lower surface electromyographic (EMG) activity [37] and motor unit discharge rates [38] have been observed in conjunction with a larger and distinct activation of the motor cortex [39, 40]. A larger voluntary activation deficit observed with maximal eccentric versus concentric contractions [41, 42] indicates a protective spinal

inhibition of eccentric force [36], especially in untrained individuals [37]. Irrespective of a lower muscle activation, more force (i.e. approximately 20-60%) may be produced during maximal eccentric versus concentric contractions [43, 44], for a lower metabolic demand [45, 46] and less acute fatigue [47, 48]. Subsequently, an acute bout of maximal eccentric contractions has been demonstrated to upregulate markers of anabolic signalling (i.e. satellite cell activation [49, 50] and molecular signalling pathways [51, 52]) and exercise induced muscle damage (EIMD) [53, 54] to a greater extent than concentric contractions. Both anabolic signalling and damage responses to eccentric contractions have been found to be especially pronounced in fast twitch muscle fibres [55-57].

Accounting for eccentric strength within a resistance training program has been demonstrated to influence the magnitude and nature of neuromuscular adaptation [58]. Compelling evidence indicates that additional loading of the eccentric phase (i.e. relative to concentric strength) within resistance training can induce greater enhancements in strength [59, 60], power [61, 62], reactive strength [62, 63], and sprinting speed [63, 64] versus traditional resistance training alone. Improvements in neuromuscular performance are proposed to result from enhancements in eccentric muscle function (i.e. a faster and more forceful eccentric phase within the SSC) [65], increased volitional agonist activation during high force tasks [66], increases in muscle cross-sectional area (i.e. hypertrophy) [67, 68], increased tendon stiffness [69], and a shift towards a faster muscle phenotype [2] via increases in muscle fascicle length [70], preferential fast twitch fibre hypertrophy [71-74], and possibly an increase in Type IIx fibre composition [75]. In addition, there is evidence that faster eccentric contraction speeds (i.e. tempos) may elicit greater improvements in muscle properties, strength, power, reactive strength and sprinting performance than slower eccentric speeds [63, 75-77]. In summary, there is clear evidence to suggest that eccentric muscle function plays an integral role in a range of athletic performance tasks, and eccentric training modalities can elicit superior enhancements in neuromuscular qualities underpinning athletic performance.

1.2 Rationale

The integral role of eccentric muscle function in fast SSC function and the characteristics of this contraction type have important implications for two aspects of athletic performance; 1) performance of high force locomotive tasks such as sprinting, and 2) enhancement of physical performance via novel resistance training strategies. In addition to addressing gaps in the literature with scientific rigour, this research was intended to directly influence the practice of High Performance Sport New Zealand (HPSNZ) support staff. Therefore, research directions were driven by a combination of identified gaps in knowledge, and the needs of strength and conditioning practitioners. Three primary areas were identified which subsequently generated a rationale for further investigation:

1. It remains challenging to assess multi-articular eccentric strength and eccentric muscle function under SSC conditions in practical settings. Previous research [44, 78] has predominantly used single joint isokinetic dynamometry to measure maximum eccentric strength which may be inaccessible to the practitioner, and has limited validity in informing the role of eccentric strength in functional performance [79]. Furthermore, protocols which have assessed maximal eccentric strength under isoinertial conditions [43, 80] have relied upon the subjective interpretation of failure to control an external load, which may introduce intra- and inter-rater measurement error. High force fast SSC function on the other hand is typically inferred from the RSI measure during drop jumping and hopping tasks [16]. The RSI is a useful performance measure; however, it does not delineate the relative contribution of eccentric (i.e. braking) and concentric (i.e. propulsive) phase characteristics during ground contact to performance under SSC conditions. Therefore, novel assessment methods are necessary to provide insight into eccentric muscle function under practically relevant conditions.

2. While it is believed that eccentric phase characteristics play an important role in SSC performance [4, 14], there remains little experimental data corroborating the supposition that eccentric muscle function contributes to reactive strength, leg spring stiffness regulation and performance in a rapid high force locomotive task

such as sprint running. Further research is therefore necessary to elucidate the role of maximum eccentric strength and eccentric muscle function under fast SSC conditions in reactive strength and sprinting performance.

3. The effects of chronic eccentric resistance training on neuromuscular qualities and performance has been extensively investigated [58]. However, few studies have recruited well trained athletes undertaking a broader physical preparation program. It has also been identified that the eccentric contraction velocity (i.e. slow or fast tempo) implemented within training can influence the nature and magnitude of neuromuscular adaptation. It is less clear how the manipulation of this variable may influence the adaptive response within the aforementioned broader physical preparation program of trained athletes. Further research is therefore necessary to identify how an eccentric training intervention influences neuromuscular qualities and performance in trained athletes attempting to concurrently develop multiple components of performance in an ecologically valid (i.e. practical) setting.

1.3 Purpose

The overall purpose of this thesis was to elucidate the role of eccentric muscle function and training in athletic performance. In addition to addressing the gaps in the literature with scientific rigour, this research was intended to directly influence the practice of support staff working within HPSNZ.

Therefore, the specific objectives of this thesis were;

1. Develop practically relevant and reliable assessments of eccentric muscle function in trained athletes.
2. Investigate the role of eccentric muscle function on measures of reactive strength and sprinting performance in trained athletes.
3. Investigate the effects of chronic eccentric resistance training on neuromuscular qualities and athletic performance in trained athletes undertaking a broader physical preparation program.

1.4 Significance of Research

There is substantial interest in understanding potential mechanisms contributing to athletic performance, and subsequently, the development of targeted training protocols which may enhance athletic performance. It remains challenging to assess eccentric muscle function in practical settings, and therefore the development of reliable measures of eccentric strength and muscle function under SSC conditions is of substantial interest to researchers and practitioners working with trained athletes. There are few studies directly linking eccentric strength and eccentric phase characteristics under SSC conditions with measures of athletic performance in highly trained athletes. Reactive strength is widely considered to be an important performance quality and is typically assessed via the RSI in athlete testing. Although the RSI is a useful measure that reflects an athlete's capability to rapidly absorb large eccentric (i.e. braking) forces and subsequently produce large concentric (i.e. propulsive) forces, the relative contribution of braking and propulsive phase kinetic characteristics to well-developed reactive strength remains unclear. This information will provide additional insight into what the RSI is measuring from a mechanical perspective, and subsequently, how to best develop this quality with training.

Similarly, it is thought that eccentric muscle function plays an important role in tolerating large vertical ground reaction forces during maximum velocity sprinting. However, there is little available evidence demonstrating an association between eccentric strength, eccentric muscle function under SSC conditions and maximum velocity sprinting ability in sprint-trained athletes. The demonstration of a link between eccentric muscle function and sprinting performance will have implications for athlete assessment, and provide a rationale for the implementation of eccentric training strategies for enhanced sprinting performance. Finally, there is a paucity of literature investigating the effects of eccentric training of varying tempos on measures of athletic performance in resistance trained athletes in an ecologically valid setting. This information will serve to bridge the gap between laboratory and practical settings and provide insight into how to best integrate eccentric training with trained athletes. In summary, there is substantial theoretical and practical significance in elucidating the role of eccentric muscle function and training in athletic performance. The present thesis addresses a number of theoretical and practical gaps within the literature. This

information will have implications for the testing and training of athletes, and therefore, direct practical application for the practitioner working with trained athletes.

1.5 Thesis Organisation

This thesis is comprised of four primary sections (Figure 1.1). The first section includes two published literature reviews. Chapter 2 is a narrative review of the literature describing the characteristics of eccentric contractions and acute physiological responses to eccentric exercise. Chapter 3 is a systematic review of original studies investigating the chronic adaptations to eccentric training, with particular reference to neuromuscular adaptations underpinning athletic performance. The second section investigates the reliability of two novel and practical assessments of eccentric muscle function. Chapter 4 describes a novel method to determine lower body eccentric strength under isoinertial conditions. Chapter 5 describes the reliability of a drop jump (DJ) force-time phase analysis that provides insight into discrete eccentric (i.e. braking) and concentric (i.e. propulsive) phase contributions to reactive strength performance. The third section comprises two cross-sectional investigations which determined the contribution of eccentric muscle function to athletic performance. Chapter 6 investigates the braking and propulsive phase kinetic determinants of reactive strength (i.e. fast and high force SSC function) in highly trained sprint athletes in comparison to a non-sprint trained control group. Chapter 7 investigates the role of eccentric strength, reactive strength (including eccentric muscle function under SSC conditions) in maximum velocity sprinting performance, with particular reference to the ability to regulate the stiffness of the leg spring during ground contact. A cohort of highly trained sprint athletes expected to exhibit well developed sprinting capabilities were compared with a cohort of trained team sport athletes. The fourth section (Chapter 8) investigates the effects of an eccentric training integrated within a broader physical preparation program on strength, power and speed in resistance trained team sport (i.e. Rugby Union) athletes. The final section (Chapter 9) provides a general summary of the thesis, a final conclusion and practical applications. With the exception of section two (Chapters 4 and 5), each chapter has been submitted as a stand-alone publication within a peer-reviewed journal.

Therefore, all chapters submitted for publication are presented in the format of the given journal.

The Role of Eccentric Muscle Function and Training in Athletic Performance

Chapter 1: Introduction

Reviews of the Literature

Chapter 2: Eccentric exercise: physiological characteristics and acute responses
Sports Medicine. 2017; 47(4):663-675.

Chapter 3: Chronic adaptations to eccentric training: a systematic review
Sports Medicine. 2017; 47(5):917-941.

Assessing Eccentric Muscle Function

Chapter 4: A novel assessment of isoinertial eccentric strength

Chapter 5: The reliability of a drop jump phase analysis

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Chapter 6: Kinetic determinants of reactive strength in highly trained sprint athletes
Journal of Strength and Conditioning Research. 2018; 32 (6):1562-1570.

Chapter 7: Eccentric and reactive strength contribute to stiffness regulation and maximum velocity sprinting performance in team sport and highly trained sprint athletes

The Effects of Eccentric Training on Athletic Performance

Chapter 8: Effects of accentuated eccentric loading on muscle properties, strength, power and speed in resistance-trained rugby players
Journal of Strength and Conditioning Research. 2018, 32 (10):2750-2761.

Chapter 9: General Summary, Conclusion and Practical Applications

Figure 1.1. Thesis organisation.

Eccentric Exercise: Physiological Characteristics and Acute Responses

2.0 Lead Summary

It has been identified that eccentric muscle function and training has implications for athletic performance due to the unique characteristics of this form of muscle action. Therefore, the purpose of this review was to provide a comprehensive a summary of the literature pertaining to eccentric contractions and eccentric exercise. This information provides important insight into the mechanisms underpinning a novel adaptive signal with chronic eccentric training. As noted, an eccentric contraction involves the active lengthening of muscle under an external load. The molecular and neural mechanisms underpinning eccentric contractions differ to those of concentric and isometric contractions and remain less understood. A number of molecular theories have been put forth to explain the unexplained observations during eccentric contractions that deviate from the predictions of the established theories of muscle contraction. Postulated mechanisms include a strain-induced modulation of actin-myosin interactions at the level of the cross-bridge, the activation of the structural protein titin, and the winding of titin on actin. Accordingly, neural strategies controlling eccentric contractions also differ with a greater, and possibly distinct, cortical activation observed despite an apparently lower activation at the level of the motor unit. The characteristics of eccentric contractions are associated with several acute physiological responses to eccentrically-emphasised exercise. Differences in neuromuscular, metabolic, hormonal and anabolic signalling responses during, and following, an eccentric exercise bout have frequently been observed in comparison to concentric exercise. Subsequently, the high levels of muscular strain with such exercise can induce muscle damage which is rarely observed with other contraction types. The net result of these eccentric contraction characteristics and responses appears to be a novel adaptive signal within the neuromuscular system.

2.1 Introduction

An eccentric muscle contraction refers to a muscle activity that occurs when the force applied to the muscle exceeds the momentary force produced by the muscle itself and results in a lengthening action (i.e. work is done on the muscle) [3]. The absorbed mechanical energy may be dissipated as heat in a dampening manner, or alternatively, the energy may be recoverable and added to the active force produced during subsequent concentric action [2, 3]. In the latter manner, the muscle-tendon system functions as a spring when active muscle lengthens before subsequent shortening. The coupling of eccentric with concentric muscle actions is referred to as the SSC; a phenomenon ubiquitous to efficient and powerful movements [3]. Despite the importance of eccentric muscle function to human movement the mechanisms underpinning eccentric contractions remain to be determined. While concentric and isometric contractions are well described by the molecular theories of muscle contraction first described by Huxley [27] and Huxley [28], the mechanics of eccentric contractions are not [26]. A number of nuanced molecular mechanisms and neural strategies have been proposed to account for unexplained observations during eccentric contractions. A growing body of evidence indicates that eccentric-emphasised exercise can elicit acute responses which differ from concentric-only or traditional mixed exercise. In particular, eccentric resistance exercise which accounts for eccentric strength (i.e. is not constrained by concentric strength) appears to have a potent effect on a number of physiological variables underpinning a novel adaptive response. The purpose of this review is to describe the current theories which seek to explain the unique physiological characteristics of eccentric contractions. The novel responses to eccentric exercise will be described, with particular reference to differences to concentric or traditional resistance training. Therefore, this review describes the specific molecular and neural characteristics of eccentric muscle actions and also provides the current state of knowledge regarding some of the acute responses to eccentric exercise, including neuromuscular, cardiorespiratory, hormonal and molecular aspects.

2.2 Characteristics of Eccentric Contractions

2.2.1 Molecular characteristics

During muscle contraction the filaments actin and myosin remain at a constant length and a change in fibre length is achieved via a change in overlap between the two in a sliding motion; hence the sliding filament theory of muscle contraction [27, 28]. The driving force for the sliding motion is generated by myosin cross-bridges where the two filaments overlap. Myosin heads repeatedly interact with binding sites on actin, with each contact contributing to the force developed [32]. The performance of any one bridge is believed to remain uninfluenced by the activity of other bridges [81], and the number of cross-bridges formed determined by the magnitude of contractile activation and amount of actin-myosin overlap (i.e. the length-tension relationship). This process effectively explains both concentric and isometric muscle actions [32]. In the case of isometric actions where there is no change in muscle length, cross bridge turnover does still occur with bridges spontaneously dissociating and being replaced by new bridges maintaining the net cross bridge formation, and energy expenditure occurs in the absence of external work [81, 82]. When the force applied is sufficient to overcome the external load the muscle can shorten with thin filaments sliding towards the centre of thick filaments. With increasing speed this process decreases exposure time of myosin heads to actin binding sites [81], and thus reduces the number of cross-bridges that may be formed (i.e. a force-velocity relationship). Unfortunately, the cross bridge theory alone is inadequate in explaining the greater force produced during active lengthening [29], the time-dependent residual force enhancement [30], and the reduced energy expenditure of eccentric contractions [31, 82].

The increased force production during lengthening contractions above isometric force capabilities may be related to differences in the number of attached cross-bridges and mechanical detachment of active cross-bridges. It has been proposed that the activation of the second (i.e. partner) head of a myosin molecule to actin increases the total number of active cross-bridges [29]. During isometric and concentric contractions only one myosin head is bound, whereas the increased strain on a single myosin head during lengthening contractions may facilitate the activation of the second head [29]. This

mechanism would lead to twice the number of active cross-bridges during active lengthening and could be increasingly utilised with increasing contraction velocity [29]. It has further been postulated that cross-bridges do not complete a full cycle during eccentric contractions [83]; they become suspended in an active state bound to actin and become forcibly detached followed by a rapid re-attachment [84]. Because a full cross-bridge cycle is not completed less ATP is required to maintain force [84]. Linari and colleagues [83] also demonstrated that while fast myosin heavy chain (MHC) isoforms produced 40-70% higher isometric force than slow isoforms, the slow isoform produced similar forces during lengthening. The kinetic and mechanical properties of actin-myosin interactions therefore appear to be independent of MHC isoform under lengthening conditions [83].

The greater force achieved during isometric contractions immediately following eccentric contractions indicates that passive factors beyond active cross bridge mechanisms may underpin the observations that are not accounted for by the cross bridge theory of contraction [34]. The passive component is postulated to be related to a change in stiffness of the molecular spring titin [85, 86]. Herzog [34] cites three theories to explain the residual force enhancement phenomenon; 1) an increase in active force of cross bridges, 2) a structural non-uniformity across the length-tension curve, and 3) the engagement of passive structures. Studies have demonstrated that the predictions of the first two theories fail [34, 87]. A passive mechanism for force enhancement remains plausible and may better reconcile experimental findings [34]. It is believed that a passive structural element within the sarcomere, and specifically the structural protein titin, is a key factor in the residual force enhancement with eccentric contractions [26]. Titin is the largest protein currently known in the natural world [88], and is an important structural component of the muscle cytoskeleton. Titin spans a half sarcomere inserting into a Z-band on one end and the M-line at the other, and has spring-like properties in the I-band region [34, 89] (Figure 2.1). Titin's passive force is directly related to sarcomeres and muscle length, is in parallel with the cross-bridge forces, is strengthened when cross-bridge forces become weak, and provides stability to sarcomeres [34, 88, 90, 91]. Therefore titin is logically posited as an important contributor to the regulation of muscle force [32].
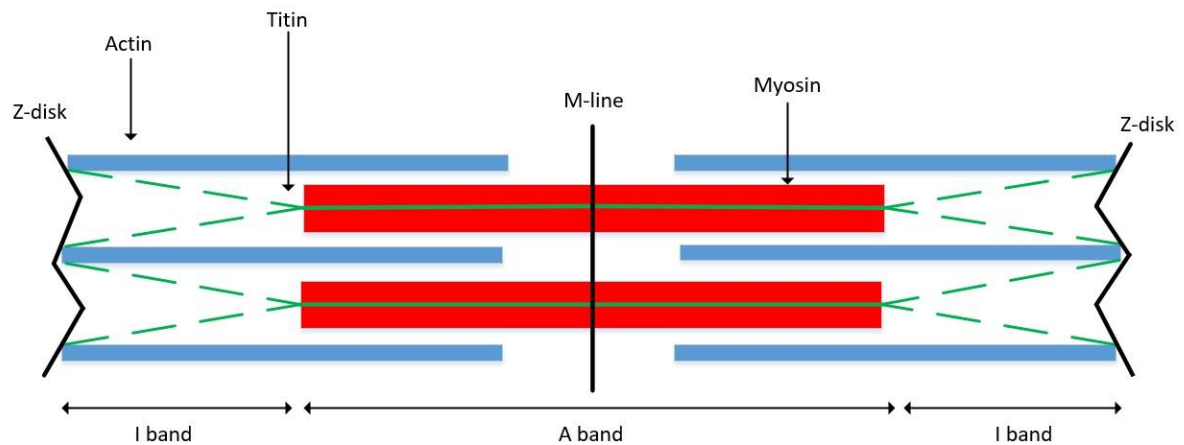
Figure 2.1. Schematic representation of a skeletal muscle sarcomere.

A three-filament model of contraction has been proposed with actin and myosin retaining their established roles; but titin additionally acts as a spring that binds calcium upon activation and binds to actin upon cross-bridge attachment [34]. Calcium binding to certain regions of titin has been demonstrated to increase its stiffness and subsequently increase force upon lengthening [34, 88, 92, 93]. While the binding of titin to actin has not been directly demonstrated *in situ*, the proposition is supported by observations that even in the presence of calcium activation, increases in titin force are dependent on cross-bridge activation [88]. Further to this, Nishikawa and colleagues [33] propose a 'winding filament' hypothesis whereby cross-bridges serve as rotors that wind titin on actin, storing elastic energy in the proline-glutamate-valine-lysine (PEVK) region of titin which can subsequently contribute to the energy recovered during active shortening. Further research is necessary to verify both the three-filament model and the winding filament hypothesis, but both serve as promising avenues in explaining phenomena of eccentric contractions.

In summary, the sliding filament theory fails at a number of levels to reconcile aberrant experimental observations related to the greater force produced during active lengthening, residual force enhancement and lower energy expenditure of eccentric

contractions. In addition to the theory of mechanical cross bridge detachment the three-filament model and winding filament hypothesis may provide additional insight into many of the unexplained observations associated with eccentric contractions, with titin probably being the long sought 'skeletal muscle spring'.

2.2.2   *Neural characteristics*

The neural strategies controlling eccentric contractions appear to be unique in comparison with concentric and isometric contractions [35, 66]. The differences between contraction types under maximal conditions have been investigated using three primary methods: surface electromyography (EMG), twitch interpolation, and single motor unit assessment [36]. When muscle activity is inferred from surface EMG the observed amplitude has been demonstrated to be lower during maximal eccentric contractions than maximal concentric and isometric contractions [37, 41, 94, 95], although not in all cases [96-98]. This difference appears to be more pronounced in untrained individuals and may be attenuated with heavy load resistance training [37, 41]. The twitch interpolation technique has been used to assess the discrepancy between maximal voluntary contraction (MVC) and maximal muscle activation via superimposed electrical stimulation [99]. A greater voluntary activation deficit has been found in eccentric compared with concentric contractions [41, 42, 100], although this discrepancy can be removed with resistance training (Figure 2.2) and may be muscle group dependent [36, 37, 41, 66]. The assessment of single motor unit activity also indicates lower and more variable motor unit discharge rates during maximal eccentric versus concentric contractions [36, 38]. In effect, untrained individuals display an inhibited voluntary activation during maximal eccentric contractions, which is believed to be primarily constrained by mechanisms that establish motor unit discharge rates [36, 101].
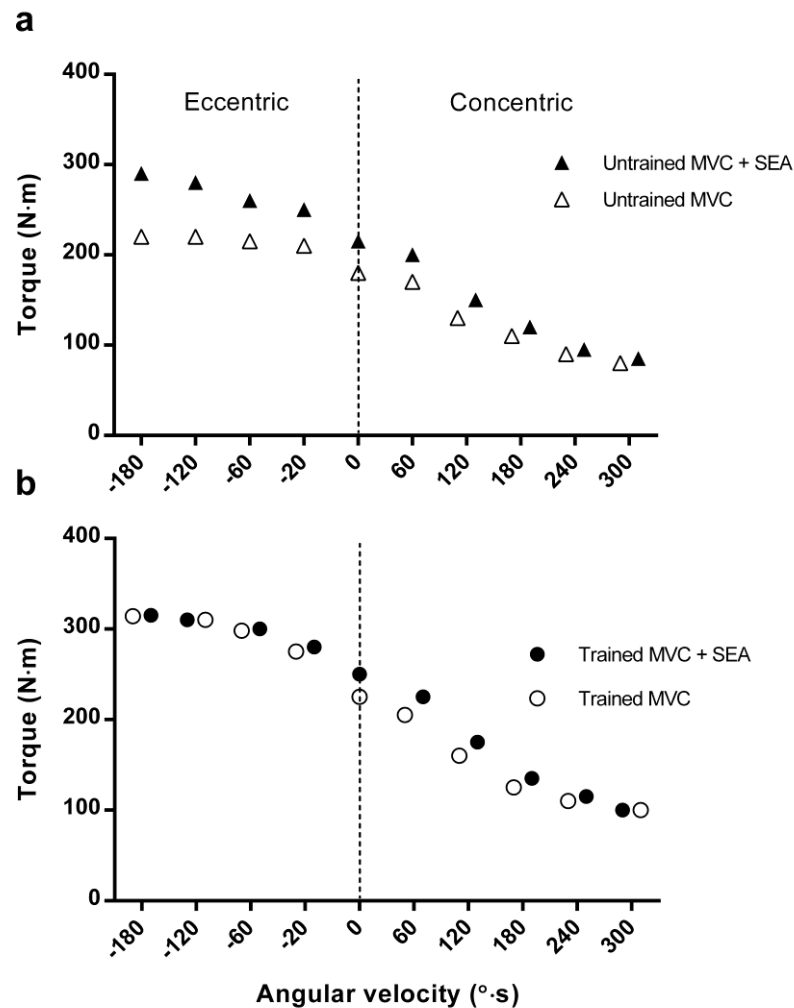
Figure 2.2. Representative torque-angular velocity curve during a single joint isokinetic movement (i.e. knee extension) for (a) an untrained and (b) a trained participant during a maximal voluntary contraction (MVC) and a MVC with superimposed electrical activation (MVC + SEA). Data from Amiridis et al. (1996) [41].

The greater intrinsic force capacity of muscle during eccentric contractions means fewer motor units are required to attain a given absolute force and a lower net activation is required for a given submaximal load [36]. The strategies of muscle control during submaximal eccentric contractions can also differ from concentric contractions. It has been demonstrated that high-threshold motor units can be selectively recruited during eccentric contractions, particularly at fast eccentric velocities [102]. It has further been shown that preferential recruitment of predominantly fast-twitch synergists can occur

with increasing eccentric contraction velocities [103, 104]. However, most studies have found little difference in motor unit recruitment between contraction types [105-108]. Indeed, a progressive de-recruitment of the highest threshold motor units may occur during submaximal eccentric contractions. This observation aligns with Henneman's size principle [109]. Fewer and/or smaller motor units are required to match the lower force demands during eccentric contractions. A reduced motor unit discharge rate in conjunction with progressive de-recruitment during eccentric contractions supports the notion of a general size-related recruitment strategy irrespective of contraction type [35, 36], although further research is necessary to elucidate the adjustments that can occur during fast eccentric contractions and differing mechanical conditions [101].

Mechanisms underpinning the unique neural strategies during eccentric contractions are not well understood but are likely a combination of supraspinal and spinal factors [101]. Cortical excitability appears to be enhanced during eccentric contractions and a greater brain area is involved irrespective of the load condition and lower motor unit activity [39, 40]. Indeed, efferent motor output is not only regulated by central descending pathways but also modulated by inflow from Golgi organs, muscle spindles, muscle afferents, and recurrent inhibition from Renshaw cells [66]. Spinal inhibition is believed to be a primary mechanism underpinning reduced motor activity during eccentric contractions [36]. The enhanced cortical excitability and descending drive has been postulated as a compensatory response to such inhibition [110]. Motor evoked potentials in response to transcranial magnetic stimulation (TMS) have been found to be smaller during eccentric contractions [110-112], probably as a result of both pre- and post-synaptic mechanisms at the level of the motoneuron [36, 110]. Furthermore, depressed Hoffman reflex (H-reflex) amplitude is indicative of a disfacilitation of the motoneuron pool during eccentric contractions [96, 101]. Given a similar response across maximal and submaximal eccentric conditions [113], a tension-related Golgi tendon organ inhibition is unlikely to be a primary factor [101], while a clear reciprocal inhibition has also yet to be demonstrated [36]. Experimental data demonstrating recurrent inhibition are lacking, but this is a known mechanism for reducing motor unit discharge rates and stands as a possible mechanism in the reduced motor response during eccentric contractions, especially in untrained subjects [36, 101].

In summary, eccentric contractions exhibit unique neural strategies compared with concentric and isometric contractions under both maximal and submaximal conditions. Differences appear to be primarily mediated by spinal inhibition, although further research is necessary to determine the precise mechanisms. Heavy load resistance training has been established as an efficacious strategy in attenuating reflex inhibition during maximal eccentric contractions and can therefore induce improvements in neuromuscular activation and maximal eccentric strength [101].

2.3 Acute Responses to Eccentric Exercise

2.3.1 Neuromuscular responses

The magnitude of joint moment is greatest during eccentric contractions, exceeding the isometric moment by 30-40% [114]. The *in vivo* difference is smaller than previously demonstrated in single muscle fibres [115], and may be due to the greater voluntary activation deficit with eccentric contractions [95], particularly in untrained subjects [37, 41] (Figure 2.2). Indeed, isometric force can occasionally exceed eccentric force at a given joint angle [116], probably due to difficulties with full activation during slow eccentric velocities and large ranges of motion [117]. When using dynamic isoinertial loads during conventional resistance exercises individuals are 20-60% stronger eccentrically than concentrically [43], which aligns with findings using isokinetic dynamometry [44]. Females can exhibit a greater difference between eccentric and concentric strength [43], possibly due to differences in elastic energy storage, motor unit recruitment and inhibition of maximal force [116, 118]. Unlike the force-velocity relationship during concentric contractions, force during eccentric contractions increases with velocity up to a certain point, after which it levels off, or declines slightly [114, 118, 119]. The ability to fully activate muscle in resistance trained subjects may facilitate the increase in force with increasing eccentric contraction velocities [41]. It is presently unclear whether such a force-velocity relationship is influenced by sex, or the muscle group assessed [116, 118]. EMG activity does not appear to vary with eccentric contraction velocity, indicating that factors other than motor unit recruitment (e.g. viscoelastic properties and non-contractile elements) contribute to an increased force production capacity that can be observed with increased velocity [103]. The differences

in force-velocity relationships between concentric and eccentric contractions mean that the discrepancy between moments becomes even greater with increasing angular velocities [114].

The unique neural strategies underpinning eccentric contractions can also affect the control of muscle force. The majority of research has investigated slow finger movements that may not translate to exercise related tasks, but the control of knee extensor torque has been investigated in healthy young participants [120, 121]. Peak force variability (i.e. CV of the % MVC) appears to be higher during anisometric contractions compared with isometric contractions [121], although in a follow up study Christou and Carlton [120] found higher peak force variability during eccentric contractions at high contraction velocities. Furthermore, at low levels of force the time to peak force was demonstrated to be more variable during eccentric contractions [120]. The differences in motor output variability have been attributed to the greater motor unit discharge rate variability during eccentric contractions [38, 101] in conjunction with a possible selective recruitment of high threshold motor units [102]. Interestingly, the control of force during eccentric cycling has been found to be highly correlated with world ranking in elite alpine slalom skiers [2], which may have implications for the relevance and trainability of eccentric force control to the athletic population.

In summary, individuals are typically stronger eccentrically than concentrically and force production may not be impaired with increased contraction velocities. Age, sex and training history all appear to influence the eccentric to concentric strength ratio and force-velocity relationship [122]. The fine control of eccentric muscle contractions may be lower than concentric contractions, which could have implications in the performance of eccentric exercise modalities. It remains to be demonstrated whether this is a trainable quality, or relatively innate to elite athletes involved in eccentrically biased sports.

2.3.2 Cardiorespiratory and fatigue responses

For a given mechanical power output eccentric exercise is less metabolically demanding than concentric exercise [45, 46], with fewer motor units required for the same work rate [123]. Subsequently, oxygen consumption ($\dot{V}O_2$) is lower during downhill walking versus uphill walking [124], downhill running versus uphill running at a given velocity [125], and during eccentric cycling versus concentric cycling at a given power output [45, 123, 126-128]. Furthermore, energy consumption during combined concentric and eccentric resistance exercise appears to be mostly related to the concentric component [129]. The ratio of $\dot{V}O_2$ for concentric versus eccentric exercise always exceeds 1.0, although the precise value will depend on the modality, movement velocity, and method of assessment [114, 130]. The observation of an increased ratio with increased movement velocity [131] may be related to the differences in force-velocity relationships between contraction types [114]. Per unit of muscle activation (i.e. EMG), $\dot{V}O_2$ can be around three times lower during eccentric contractions [131]. Independent of any change in anaerobic metabolism [132], eccentric exercise (i.e. eccentric cycling and downhill walking) requires 4-5 times less oxygen [123], and a markedly lower cardiac output ($\dot{Q}$) and heart rate (HR) response to concentric exercise at similar mechanical workloads [45]. The lower metabolic intensity of eccentric cycling has been demonstrated to result in lower perceived exertion, blood lactate accumulation, energy expenditure and carbohydrate oxidation, and higher fat oxidation than concentric cycling at a matched mechanical workload [46, 133]. To attain a similar $\dot{V}O_2$ during cycle ergometry a substantially higher mechanical power output is necessary; under these conditions $\dot{Q}$ and HR are higher than at a similar $\dot{V}O_2$ for concentric cycling [45, 123]. Above a certain threshold (i.e. >1 L/min), $\dot{Q}$ can be 27% higher and HR 17% higher for a given $\dot{V}O_2$ during eccentric exercise [45], accompanied by a higher rating of perceived exertion [123]. Below this threshold eccentric and concentric cycling at similar metabolic intensities result in a similar HR response [134]. Pulmonary ventilation ($\dot{V}_E$) may also be higher during eccentric exercise (i.e. downhill walking) for a given $\dot{V}O_2$ [135], which is probably due to larger muscle forces eliciting a higher neurogenic respiratory drive and $\dot{V}_E$ response [114]. Under such circumstances eccentric exercise is also more heat stressful (e.g. 2°C higher muscle temperature) instigating a thermoregulatory response which can affect muscle metabolism and oxygen dissociation kinetics [114, 135, 136]. It should be noted that the relationship between $\dot{V}_E$

and $\dot{V}O_2$ may be modality dependent as eccentric cycling has been reported to elicit an equivalent $\dot{V}_E$ to concentric cycling for a given $\dot{V}O_2$ [127]. The higher mechanical loads with eccentric cycling require a postural bracing via activation of the upper extremities which may impair rib cage expansion, lung volume displacement and therefore $\dot{V}_E$ [127].

Fatigue seems to be less apparent during isokinetic eccentric exercise compared with isokinetic concentric exercise [47, 48]. Higher average mean and peak forces have been found across 100 maximal isokinetic eccentric contractions of the knee extensors in conjunction with a higher total work and lower fatigue index [48]. As with concentric fatigue there are a number of central and peripheral sites which can contribute to an impaired motor output [48], but fatigue resistance during eccentric actions may be particularly influenced by the capacity to maximally recruit muscle [47]. Aligning with this hypothesis Hortobagyi et al. [137] found that increasing eccentric strength (i.e. a 42% increase) somewhat attenuated (i.e. ~10%) the fatigue resistance during an eccentric exercise protocol, albeit non-significantly. Irrespective of the lower energy expenditure and fatigue during eccentric exercise, it appears that the elevated energy expenditure following exercise (e.g. 48-72 hours) is directly related to the eccentric contribution and may be due to muscle damage [130, 138, 139]. It should be noted that eccentric cycling exercise has been demonstrated to induce muscle damage without influencing resting energy expenditure in the days following the bout [46, 133], and therefore further research is necessary to draw firm conclusions.

In summary, eccentric exercise is less metabolically expensive at matched workloads and a substantially higher workload is necessary to elicit a comparable $\dot{V}O_2$ during downhill running and eccentric cycling. Furthermore, the energy expenditure during resistance exercise may be predominantly attributed to the concentric phase, while fatigue is substantially lower with eccentric versus concentric contractions. It may therefore be possible to attain higher session workloads with eccentric exercise in comparison to concentric or mixed exercise.

2.3.3 Hormonal responses

Eccentric resistance exercise has been found to elicit comparable and lower testosterone and growth hormone (GH) responses respectively than concentric exercise at the same absolute workload [140]. Exercise at the same absolute load across contraction types precludes an equivalent relative intensity, and it was subsequently demonstrated that the GH response was similar during both concentric and eccentric resistance exercise when accounting for eccentric strength [141]. Kraemer and colleagues [142] reported that eccentric resistance exercise elicits similar GH and testosterone responses to concentric exercise at approximately equivalent relative intensities. Insulin-like growth factor-I (IGF-I) appears to be more responsive to the higher mechanical tension with eccentric contractions and has been found to be higher 48 h following eccentric exercise versus concentric exercise [143], although the body of evidence suggests little difference [142]. Most studies have compared concentric-only to eccentric-only protocols which may not, anecdotally at least, represent the diversity of approaches used within the field. Ojasto and Hakkinen [144] investigated the effects of an eccentric overload applied on top of a typical concentric load (i.e. with the addition of weight releasers which unhooked at the bottom portion of the lift) during a bench press. When eccentric and concentric loads were used equivalent to 90% and 70% of the concentric one repetition maximum (1RM) respectively the highest blood lactate and GH responses were observed [144]. It was proposed that this loading scheme allowed an optimal combination of intensity and volume as fewer repetitions were achieved with eccentric and concentric loads of 100% and 70% 1RM with a concomitantly attenuated GH response [144]. Irrespective of contraction type it appears that a slow contraction velocity maximises the GH response, while IGF-I and testosterone seem to be less influenced by time under tension [142]. Although much of the available data comes from untrained subjects [142], Calixto et al. [145] demonstrated in resistance trained participants a higher GH response with slower eccentric velocities compared with fast eccentric velocities. The blood lactate response was also substantially higher with slow contractions which implies a relationship between the GH response and the anaerobic glycolytic contribution to the exercise bout [145]. Indeed, less lactate accumulation has been observed following eccentric versus concentric resistance exercise at similar absolute workloads [140] and the magnitude of the difference is partly attenuated with matched relative intensities [141]. Eccentric

contractions do not appear to elicit notably different insulin or cortisol responses from concentric contractions, although most studies have used matched absolute loads and therefore the influence of relative intensity remains less clear [142].

In summary, the hormonal response does not appear to be largely influenced by contraction type but rather a combination of load and time under tension. Whether the acute hormonal response to exercise mediates long term adaptations remains contentious [146], and is perhaps less important than other transcriptional factors.

2.3.4 Molecular responses

The upregulation of satellite cell activity, in conjunction with other transcriptional pathways, has an important role in the adaptive response to training [147]. Satellite cells are mitotically and metabolically quiescent precursor (i.e. stem) cells that reside between the basal lamina and the sarcolemmal membrane of skeletal muscle [55]. With an appropriate stimulus (i.e. muscle damage from injury or exercise) satellite cells are activated, proliferate and migrate to areas of damage, fusing to surrounding muscle [49, 148]. Satellite cells produce daughter cells and subsequently new myonuclei within muscle which increases the capacity for protein synthesis [50]. Although resistance training has been well established to increase myonuclear and satellite cell content [55], Hyldahl et al. [49] showed that maximal (i.e. isokinetic) eccentric but not concentric resistance exercise elicited satellite cell proliferation acutely following exercise. They suggested that the muscle damage associated with the eccentric component may be the primary driver activating the satellite cell gene pool [49]. This aligns with the finding that the cytokine interleukin-6, a signalling molecule for satellite cell activation [148], increases in the acute period following eccentric exercise with a role in the immediate immune response to muscle damage [149]. In the 24 h period following a single bout of maximal isokinetic eccentric exercise satellite cell content can increase from 30-150% [50, 55, 148], and while satellite cell activity has been demonstrated to increase from 24-72 h [49, 148], other markers (e.g. natural cell adhesion molecule and the foetal antigen 1) can be elevated for up to eight days following an eccentric exercise bout [150]. There is also evidence indicating a preferential satellite cell increase in fast twitch muscle fibres. A single bout of maximal eccentric exercise was found to induce a

significant increase in satellite cell activity in type II fibres in contrast to no apparent change in type I fibres [55].

Protein synthesis is a key variable regulated in the post-exercise period [147]. Maximising net protein accretion (i.e. protein synthesis - protein breakdown) will benefit the hypertrophic response to a given training protocol [51]. Force generation and stretch have been established to activate protein synthesis [147], and given that eccentric contractions involve both, it is plausible that there is an additive effect beyond what could be attained with each mechanism in isolation [52]. Indeed, Z-disk streaming with eccentric resistance exercise is proposed to be an important factor in the hypertrophic response due to the presence of phospholipase D which may mediate stretch-induced anabolic signalling [56, 151]. Changes in protein synthesis rates are mediated by the activation of enzymes which control protein translation into muscle [52], and intracellular signalling has been found to be influenced by contraction type [152, 153]. Matched for total work, maximal isokinetic eccentric exercise can induce a more rapid rise in myofibrillar protein synthesis and subsequently a greater myofibrillar protein accretion in the post-exercise period (i.e. 8.5 h) compared with maximal concentric exercise [51]. A modest bout of eccentric exercise (i.e. 4 x 6 maximal isokinetic contractions) can upregulate p70 S6 kinase ($p70^{S6k}$) activity and thus protein translation initiation in the absence of nutritional intake for at least 2 h, while maximal concentric exercise may not [52]. The activation of $p70^{S6k}$ is an important step in the P13K/Akt/mTORCI/$p70^{S6k}$ muscle hypertrophy signalling pathway which is known to increase protein synthesis in response to mechano growth factor messenger RNA expression [151]. Variation in eccentric contraction velocity (i.e. $20°/s^{-1}$ vs. $210°/s^{-1}$) does not appear to influence the magnitude of $p70^{S6k}$ upregulation [151]. In alignment with other findings of a fibre type specific response to maximal eccentric contractions, type I and II muscle fibres may exhibit pronounced differences in $p70^{S6k}$ upregulation following eccentric resistance exercise with a substantially greater increase in type II fibres [56]. The striated muscle activator Rho signalling pathway assists with the transcription of specific myofibrillar genes in response to an acute exercise bout and is also upregulated to a greater extent with maximal eccentric contractions [152]. Maximal eccentric contractions can increase markers of collagen expression (i.e. transforming growth factor-β-1 [TGF-β-1]) in skeletal muscle to a greater extent than concentric

contractions in rats, although tendon collagen expression was reported to be less sensitive to contraction type than muscle [154].

In summary, muscle satellite cell activity and anabolic signalling pathways appear to be upregulated to a greater extent with maximal eccentric contractions, while there is evidence that type II fibres in particular benefit from these anabolic processes.

2.3.5 Exercise-induced muscle damage and the repeated bout effect

Fewer motor units are recruited for a given submaximal load during eccentric versus concentric contractions which implies that there will be greater force per active motor unit [130, 131]. This is related to exercise-induced muscle damage (EIMD) to recruited muscle fibres [122], while aspects of eccentric contractions not related to tension *per se* also appear to predispose to the occurrence of EIMD [53, 155]. The extent of EIMD from eccentric exercise appears to be greater with higher loads [156], fast contraction velocities [157], long muscle lengths during exercise [53], and in untrained participants [158]. EIMD is characterised by increased circulating intramuscular enzymes such as creatine kinase (CK), along with skeletal troponin I, myoglobin and MHCs [159] and is known to impair force and power production [130]. Reductions of 10-60% of MVC have been reported for up to a week following eccentric exercise [122, 160]. The magnitude of MVC impairment appears to be directly related to the number of muscle fibres with myofibrillar disruption [161]. Power output at various cycling cadences can be substantially impaired (i.e. 11-15%) for at least 48 h following an eccentric cycling bout [162], with the impairment being specific to the muscle group (i.e. knee extensors) which absorbs the most force during the particular task [155]. The reduced neuromuscular performance with EIMD may, at least partly, be underpinned by impaired sarcolemmal action potential conduction velocity [163] and transient changes (e.g. 24 h) in central nervous system activity [130]. Delayed onset muscle soreness (DOMS) refers to the dull, aching pain felt during movement or upon palpation of the affected tissue and often accompanies EIMD [164]. Muscle soreness appears in the hours following eccentric exercise, peaks after 1-3 days and disappears after 7-10 days [165]. Interestingly, DOMS appears to be independent of other markers (e.g. MVC, range of motion, and plasma CK) of EIMD [166]. The finding that DOMS can reflect

connective tissue damage and inflammation more so than muscle fibre damage and inflammation may partly explain this discrepancy [167-169].

Passive tension, swelling of muscle, and increases in muscle hardness [160] may all contribute to a reduced range of joint motion often observed following eccentric exercise [164]. Sense of force and position can both be negatively affected following eccentric exercise [53], which may have implications for the performance of sporting tasks. Running economy following a bout of downhill running can be reduced for three days [170], and may be particularly impaired at higher intensities with increased muscle fibre recruitment [171]. Gait can be affected by EIMD in a muscle specific manner [172]. Two days (i.e. 48 h) following damaging isokinetic eccentric knee extensor exercise subjects exhibited reduced knee joint range of motion during both walking and running [172]. A lack of change in stride frequency or stride time in conjunction with altered pelvic kinematics suggests subjects modulated gait in an effort to minimise pain [172], and a stiffer leg spring has been observed during SSC activities in the presence of EIMD which supports a possible compensatory stiffness modulation [173]. As noted, knee joint power is most affected following eccentric cycling (i.e. 19%), but total power is reduced to a lesser extent (i.e. 11%) indicating that multi-joint performance can be better maintained in the presence of EIMD than single-joint performance [155]. A number of metabolic consequences of EIMD have also been reported, including decreased glucose uptake and insulin sensitivity, impaired glycogen synthesis, elevated metabolic rate, and a shift towards non-oxidative metabolism [159]. Symptoms of EIMD become prominent 12-48 hours after intense or unfamiliar eccentric exercise, peaking between 24-72 hours and gradually disappearing in 5-7 days in concert with the restoration of neuromuscular capabilities [122, 130].

The pathophysiology of EIMD is not entirely understood and several theories have been proposed to explain the phenomenon. It has been disputed whether disruption to sarcomeres within the myofibrils or damage to the excitation-contraction coupling system is the primary event underpinning EIMD [54]. Proske and Morgan [54] have argued in favour of the former (e.g. the "popping sarcomere" hypothesis) and proposed that a region of instability on the descending limb of the length-tension curve is the basis for EIMD with eccentric exercise. When myofibrils are stretched while contracting, sarcomeres with an overlap closer to their optimum value resist stretch

more so than others, meaning that weaker sarcomeres take up most of the stretch. These sarcomeres become progressively weaker if this occurs on the descending limb of the length-tension curve and upon reaching their yield point will lengthen uncontrollably (i.e. "popping") to the point of no myofilament overlap [174], subsequently engaging passive structures to maintain active tension equivalent to adjacent sarcomeres [54]. Across a series of contractions an increasing number of sarcomeres (i.e. from weakest to strongest) become overstretched and may not reinterdigitate during relaxation and subsequently become disrupted [175]. With a progressive increase in overstretched and disrupted fibres, damage may spread longitudinally to adjacent sarcomeres in the myofibril and transversely to adjacent myofibrils [53]. Overstretched sarcomeres become disorganised (e.g. Z-disk streaming) leading to lesions of the sarcolemma, transverse tubule dilation, sarcoplasmic reticulum fragmentation [122], and thus disruption to excitation-contraction coupling machinery [54, 176]. Extensive damage from repeated eccentric contractions can elicit symptoms of inflammation and necrosis [130], triggering nociceptor (i.e. type III and IV afferents) stimulation and subsequently DOMS [54]. Passive tension can rise with EIMD and muscle stiffness can double, remaining elevated for around 4 days [54]. The uncontrolled release of Ca^{2+} resulting from membrane damage may elicit a low level muscle activation and subsequent rise in passive tension [54], although this process remains to be demonstrated. While both slow and fast twitch fibre types can be damaged with eccentric exercise, there is evidence to suggest that type II fibres are particularly susceptible to damage from intense eccentric exercise [57, 177]. Large fast-fatigable motor units may be more vulnerable due to their lack of oxidative capacity, a higher tension generating capacity, and/or because they have a shorter optimum length for tension [54].

The repeated bout effect refers to the phenomenon whereby the magnitude of EIMD and DOMS is progressively attenuated with repeated exposures to the same eccentric exercise bout [178]. A second similar bout elicits substantially less EIMD and DOMS [179], with the protective effects lasting from several weeks and possibly up to six months [180, 181]. Trained individuals, and particularly those engaged in eccentric exercise, are less susceptible to EIMD and the associated pathophysiological symptoms [158]. The mechanisms underpinning the repeated bout effect are not entirely clear but it appears that neural, mechanical and cellular adaptations all contribute to the adaptive response [130]. Given the unique neural strategies during eccentric contractions, it is

plausible that neural adjustments underpin the repeated bout effect [178]. Specifically, changes in activation may better distribute the fibre stresses to limit myofibrillar damage [182]. Supporting this are EMG data indicating a redistribution of stress across a greater number of fibres [137]. The observation of a protective effect on the contralateral limb with ipsilateral training is supportive of a neural component of the repeated bout effect [183], although these adjustments do not appear to completely account for the phenomenon [178]. The mechanical avenue postulates changes in passive and dynamic stiffness via adaptations to non-contractile elements of the musculoskeletal system [178]. As noted, damage to the cytoskeleton is believed to be an important determining factor in EIMD, and subsequently an increase in the structural protein desmin content has been demonstrated within 3-7 days following damaging eccentric exercise in rats [184]. The increase in desmin content is proposed to provide additional reinforcement against mechanical sarcomere strain [184]. Increases in intramuscular connective tissue may also be a protective mechanism by dissipating myofibrillar shear stresses [178]. Although it remains unclear the role of changes in tissue stiffness with the repeated bout effect as it has been found that stiffer muscles can exacerbate markers of EIMD [185].

Changes at the cellular level of the contractile machinery and in the inflammatory response to exercise may also play a role in the repeated bout effect [178]. Aligning with the popping sarcomere hypothesis, longer muscle lengths during eccentric contractions have been demonstrated as an important determinant of the extent of muscle damage. Morgan (1990) suggested the number of sarcomeres in series increases as an adaptive response to eccentric training which provides a protective effect against this mechanism of muscle damage by reducing sarcomere strain and mechanical disruption [174]. Indeed, a rightward shift of the length-tension curve can occur following damaging eccentric exercise and may be attributed to added sarcomeres in series [186, 187], although such morphological adaptations require a longer period of time to materialise (e.g. 7 days) indicating a biphasic mechanism underpinning length-tension changes [180]. Shorter term rightward shifts in the length-tension curve reflect popped sarcomeres on the descending limb, while the longer term shift is likely a protective adaptation [180]. Finally, the inflammatory response to eccentric EIMD can exacerbate damage (i.e. secondary damage) prior to any obvious recovery [188]. An attenuated inflammatory response to eccentric exercise was observed when preceded by

a training intervention which elicited an initial inflammatory response [188]. Whether this reflects a decrease in secondary proliferation damage or a reduced insult to myofibrillar elements remains to be determined [178].

In summary, EIMD associated with eccentric modalities has a number of consequences for the performance of subsequent exercise within the short term (e.g. $\leq$ 7 days). Symptoms of EIMD can be attenuated by a progressive increase in eccentric loading, or via the incorporation of other preconditioning exercises. Trained athletes are less affected by EIMD and thus a simple progressive overload will probably suffice to minimize the detrimental effects of muscle damage.

2.4 Conclusion

During eccentric contractions, the external force exceeds that produced by the muscle [2]. The molecular mechanisms underpinning eccentric contractions have yet to be confidently elucidated but recent theories have, at least partly, reconciled unexplained eccentric-related phenomena with established theories of muscular contraction. The increased force produced with lengthening contractions may be a function of mechanical detachment of cross-bridges suspended in an actively bound state [29, 83], while residual force enhancement may be explained by the passive action of titin interacting with actin and myosin [26, 33]. Unique neural strategies are apparently involved during maximal and submaximal eccentric contractions [35]; cortical excitability seems to be greater with eccentric contractions yet motor unit activity is lower [36]. Lower motor unit discharge rates suggest spinal inhibition constrains eccentric force [101], particularly in untrained subjects [41, 66]. The unique characteristics of eccentric contractions have important implications for the acute responses during and following eccentric exercise bouts. Approximately 20-60% more force can be generated during eccentric contractions compared with eccentric contractions [43, 44], yet eccentric exercise requires less energy per unit work and thus elicits a substantially lower cardiopulmonary response [45, 123]. It remains unclear whether contraction type influences hormonal responses [142], although there is some evidence indicating a larger increase in IGF-I following eccentric exercise [143]. Muscle satellite cell activity [49] and anabolic signalling pathways [51, 52, 152-154]

are upregulated to a greater extent with eccentric contractions, while fast twitch fibres appear especially responsive to these anabolic stimuli [55, 56]. Eccentric contractions are damaging to muscle and a host of consequences have been reported in the acute post-exercise period [122]. Type II fibres are seemingly most susceptible to EIMD [57, 177], which aligns with findings of increased anabolic signalling within these fibres. Repeated exposure to the same eccentric bout attenuates EIMD symptoms and has been termed the repeated bout effect [178]. The acute responses to eccentric exercise probably underpin many of the unique chronic adaptations observed with long term eccentric training.

Chapter 3

Chronic Adaptations to Eccentric Training: A Systematic Review

3.0 Lead Summary

The literature review comprising the previous chapter highlighted a substantial body of evidence describing the unique characteristics associated with eccentric contractions, and subsequently, novel physiological responses to eccentric exercise. These characteristics and responses are proposed to elicit a novel adaptive signal within the neuromuscular system which has implications for the adaptive response to chronic resistance training. Given the integral role of resistance training within athletic preparation, the purpose of this chapter was to systematically review the literature investigating the effects of eccentric training on muscle mechanical function, and MTU morphological and architectural adaptations in comparison to concentric-only or traditional (i.e. constrained by concentric strength) resistance training. Searches were performed using the electronic databases MEDLINE via EBSCO, PubMed and SPORTDiscus via EBSCO. Full journal articles investigating the long term (≥ 4 weeks) effects of eccentric training in healthy (absence of injury or illness during the four weeks preceding the training intervention), adult (17-35 years), human participants were selected for the systematic review. A total of 40 studies conformed to these criteria. Eccentric training was demonstrated to elicit greater improvements in muscle strength, although in a largely mode specific manner. Superior enhancements in power and SSC function have also been reported. Eccentric training is at least as effective as other modalities in increasing muscle cross-sectional area (CSA), while the pattern of hypertrophy appears nuanced and increased CSA may occur longitudinally within muscle (i.e. the addition of sarcomeres in series). There appears to be a preferential increase in the size of type II muscle fibres and the potential to exert a unique effect upon fibre type transitions. Qualitative and quantitative changes in tendon tissue have also been reported with eccentric training that may be related to the magnitude of strain imposed. Eccentric training is therefore a potent stimulus for enhancements in muscle mechanical function, MTU morphological, and architectural adaptations. The inclusion of eccentric loads not constrained by concentric strength appears to be superior to traditional resistance training in improving variables associated with strength, power and speed performance.

3.1 Background

Resistance training has become a ubiquitous component of physical preparation programs for athletic populations [189]. It has been well established that resistance training can improve a host of neuromuscular variables relevant to athletic performance across a continuum of strength, power, and endurance and events [189-191]. Traditional resistance training typically includes both eccentric and concentric phases of movement across a set of repetitions. Eccentric muscle actions occur when the load applied to the muscle exceeds the force produced by the muscle itself, resulting in a lengthening action [3]. Therefore, muscle forces tend to be highest during lengthening actions [44]. The prescription of load is dictated by concentric strength and thus tends to insufficiently load the eccentric phase of movement. A growing body of evidence indicates that resistance training programs which sufficiently load the eccentric phase of movement can elicit superior neuromuscular adaptations compared with concentric-only or traditional resistance training constrained by concentric strength [2, 67, 130]. The training stress and physiological strain imposed by eccentric training induces an adaptive response conducive to enhancements in muscle mechanical function, and alterations in MTU morphology and architecture. Metrics of strength, power and SSC function appear to be particularly responsive to eccentric stimuli. The purpose of this review was to systematically retrieve and collate studies which directly compared eccentric training with concentric or traditional resistance training.

3.2 Methods

The review was conducted according to the PRISMA guidelines for systematic reviews [192]. One reviewer performed initial database searches for articles investigating the chronic (i.e. ≥ 4 weeks) adaptations to eccentric training interventions on *in vivo* muscle-tendon properties and performance in human subjects (last search April 2016). Searches were performed using the electronic databases MEDLINE via EBSCO (1950-present), PubMed (1950-present) and SPORTDiscus via EBSCO (1985-present). Key search terms were grouped and searched within the article title, abstract, and keywords using the search conjunctions "OR" and "AND". Combinations of the following terms were used as search terms: "eccentric exercise", "eccentric training", "eccentric

contraction", "lengthening contraction", "negative work" and "passive work" in conjunction with the terms: "muscle", "tendon", "strength", "power", "speed", "hypertrophy", "force", "velocity" and "performance". Key journals identified were also searched using the keyword "eccentric". Furthermore, the reference lists of articles retrieved were screened for additional eligible articles. Full journal articles investigating the long term effects of eccentric training ($\geq$ 4 weeks) in healthy (i.e. the absence of injury or illness during the four weeks preceding the training intervention), adult (i.e. 17-35 years), human participants were selected for systematic review (Figure 3.1). Articles were excluded if the aforementioned criteria were not fulfilled, training was performed less than twice weekly, eccentric exercise intensity was not quantified or was below the relative concentric exercise intensity, or no concentric or traditional resistance training control group was included.
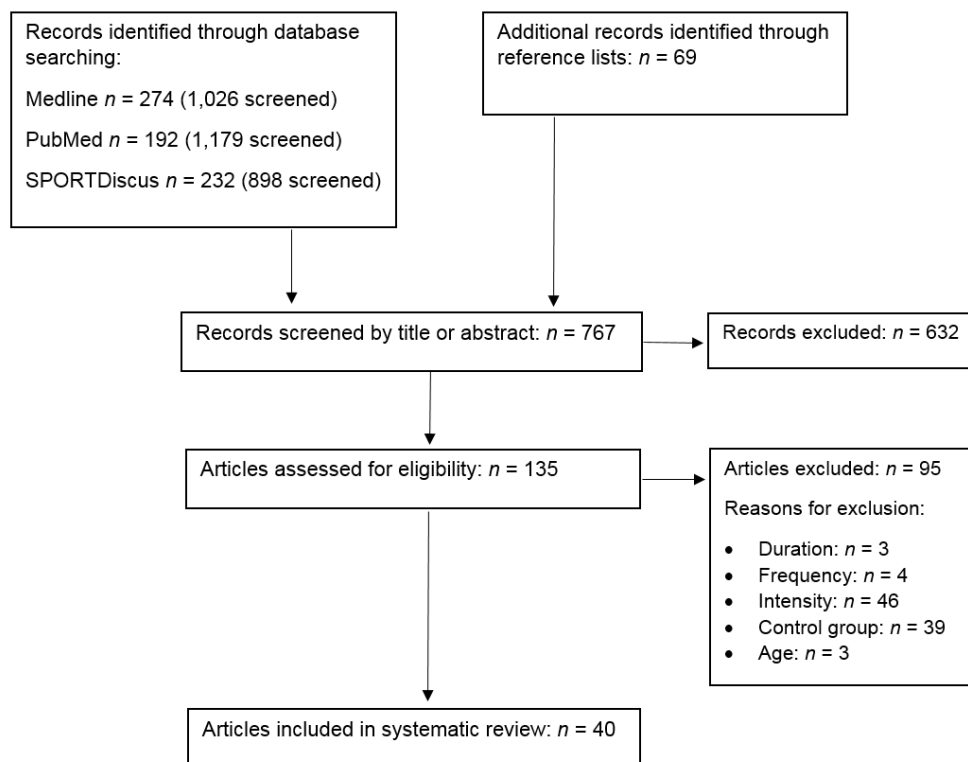
Figure 3.1. Systematic review search strategy.

3.3 Results and Discussion

3.3.1 Participant and intervention characteristics

Across the 40 studies included for review 1,150 participants (406 females and 744 males) were recruited with a mean age of 23.9 years (range: 17.6 to 35.0). The majority of investigations (32/40; 80%) recruited untrained participants, four (10%) recruited participants with resistance training experience (3 months to 1 year), while the remaining four (10%) recruited participants who were either moderately trained or participated in elite sport. The majority of investigations compared eccentric training (i.e. eccentric contractions at an intensity above the relative concentric training intensity, performed alone or in conjunction with concentric contractions) of various volumes and intensities with traditional resistance training (i.e. mixed eccentric and concentric contractions limited by concentric intensity) and/or concentric training (i.e. concentric contractions only). A non-training control group was included in 17 (43%) studies. Other training variables compared included the magnitude of overload (i.e. intensity; heavy versus light), contraction velocity (i.e. tempo; fast versus slow) and the additional effects of whey protein hydrolysate supplementation. The average intervention duration was 9.8 weeks (range: 5 to 20) with a training frequency of 2.9 sessions per week (range: 2.0 to 4.2). Single-joint movements were predominantly investigated (32 studies; 80%) and isokinetic modalities were used more (26 studies; 65%) than isoinertial.

3.3.2 Muscle mechanical function

Eccentric training has been consistently reported to increase concentric [59, 69, 71-74, 76, 193-208], isometric [61, 70, 73, 199, 203, 206, 209-211], and eccentric [68, 70, 72-74, 76, 194, 196-199, 201-206, 212-215] strength when assessed via isoinertial (i.e. repetition maximum [RM] testing) or isokinetic (i.e. maximal voluntary contraction [MVC] testing) modalities (Table 3.1). Concentric training also elicits increases in concentric [59, 68-70, 72-74, 76, 194, 196-199, 201-208, 212-214], isometric [70, 73, 199, 206, 209, 213] and eccentric [68, 73, 76, 194, 196-199, 201, 203-206, 215]

strength, while increases in concentric [71, 73, 193, 195, 200], isometric [61, 73] and eccentric strength [73] are similarly observed following traditional resistance training (Table 1). Strength increases have been proposed to be largely mode-specific [67]; and while some studies reported that eccentric training increased eccentric strength to a greater extent compared with concentric training [68, 72, 74, 196, 201, 203, 204, 212, 214], and vice versa [68, 194, 212-214], others found no differences between modalities [61, 71, 73, 193, 195, 197, 198, 200, 202, 205-209, 215, 216]. A number of studies investigating eccentric training included the concentric portion of the movement in addition to the overloaded eccentric portion [61, 71, 73, 193, 195-197, 200, 202, 208, 215, 216], which may partly explain the mixed findings compared with previous reviews which compared eccentric-only with concentric-only modalities [2, 67]. When using eccentric loads greater than maximal concentric strength (e.g. 1RM or MVC), eccentric training generally leads to greater overall strength increases (i.e. combined concentric, isometric and eccentric strength) than concentric and traditional training [59, 69, 72-74, 76, 195, 201, 203, 204, 207]. Furthermore, studies directly comparing heavier with lighter eccentric loads found that heavier eccentric training induced greater increases in eccentric strength [59, 69]. Muscle contraction velocity used within training can also influence strength adaptations and greater increases in eccentric strength have been observed with fast versus slow eccentric training [76], while increases in eccentric strength with eccentric training become more pronounced when the testing velocity corresponds to that used within training [67]. Greater increases in contralateral eccentric strength (i.e. cross-education) have been reported with fast (i.e. 180°/s) versus slow (i.e. 30°/s) eccentric training [217], although improvements can also occur following training at moderate (i.e. 60°/s) contraction speeds [218]. Fast contractions have also been proposed to allow for a greater transfer of eccentric training to concentric strength [130].

Table 3.1. Studies comparing the effects of eccentric-overload (ECC) and coupled maximal eccentric and concentric contractions (ECC+CONC) with traditional (TRAD) and concentric-only (CONC) resistance training on muscle mechanical function.

Study	Population	Muscle groups (modality)	Intervention	Training duration	Training effect (p < 0.05)
Barstow et al. 2003 [216]	ECC n = 13, TRAD n = 13, CONT n = 13, (8F, 31M); mean age: 22.2 years; training status: 3 months' resistance training.	EF (isoinertial; single-joint).	Volume: 3 sets of 8 repetitions; intensity: ECC group: 100/60% 1RM, TRAD group: 60 % 1RM; tempo: 2s ECC, 2s CONC.	12 weeks (2 sessions per week)	No differences in CONC EF strength (1RM) between ECC (16%), TRAD (14%) or CONT (10%).
Ben-Sira et al. 1995 [193]	ECC_{Heavy} n = 8, TRAD n = 8, ECC_{Light} n = 10, CONC n = 12, CONT n = 10, (48F); mean age: 21.1 years; training status: untrained.	KE (isoinertial; single-joint).	Volume: ECC_{Heavy} group: 3 sets of 5 repetitions, TRAD, ECC_{Light} and CONC group: 3 sets of 10 repetitions; intensity: ECC_{Heavy} group: 135/65% 1RM, TRAD, ECC_{Light} and CONC groups: 65% 1RM; tempo: 3s ECC, 1s CONC.	8 weeks (2 sessions per week)	Increase in CONC KE strength (1RM) with ECC_{Heavy} (23%) and TRAD (19%) versus CONT (4%), no difference between interventions.
Blazevich et al. 2007 [194]	ECC n = 11, CONC n = 10, CONT n = 9, (16F, 14M); mean age: 22.8 years; training status: untrained.	KE (isokinetic; single-joint).	Volume: 5 sets of 6 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 30°/s.	10 weeks (3 sessions per week)	Increase in CONC KE strength (MVC) with ECC (16%) and CONC (24%) versus CONT (1%), but greater increase with CONC. Increase in ECC KE strength (MVC) with ECC (39%) and CONC (36%) versus CONT (3%), no difference between interventions.
Blazevich et al. 2008 [209]	ECC n = 11, CONC n = 10, (11F, 10M); mean age: 22.8 years; training status: untrained.	KE (isokinetic; single-joint).	Volume: 5 sets of 6 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 30°/s.	10 weeks (3 sessions per week)	Increase in ISO KE strength (MVC) with ECC (10%) and CONC (13%), no difference between interventions. Increase in RFD 30 ms ($N \cdot s^{-1}$) with ECC (28%) and CONC (50%), greater increase with CONC versus ECC.
Brandenberg and Docherty 2002 [195]	ECC n = 8, TRAD n = 10, (18M); mean age: NR, university students; training status: 1 year resistance training.	EF and EE (isoinertial; single-joint).	Volume: ECC group: 3 sets of 10 repetitions, TRAD group: 4 sets of 10 repetitions; intensity: ECC group: 115/75% 1RM, TRAD group: 75% 1RM; tempo: 2s ECC, 2s CONC.	9 weeks (2.8 sessions per week)	Increase in CONC EF strength (1RM) with ECC (9%) and TRAD (11%), no difference between interventions. Increase in CONC EE strength (1RM) with ECC (24%) and TRAD (15%), but greater increase with ECC training.
Colliander and Tesch 1990 [196]	ECC+CONC n = 11, CONC n = 11, CONT n = 7, (29M); mean age: 26.3 years; training status:	KE (isokinetic; single-joint).	Volume: ECC+CONC group: 4.8 sets of 6 CONC repetitions & 6 ECC repetitions, CONC Group: 4.8 sets of 12 CONC repetitions;	12 weeks (3 sessions per week)	Increase in ECC KE strength (MVC) with ECC+CONC (36%) and CONC (19%), no change with CONT (-5%), greater increase with ECC+CONC versus CONC.

	untrained.		intensity: ECC+CONC group: ECC & CONC MVC, CONC group: CONC MVC; tempo: 60°/s.		Increase in CONC KE strength (MVC) with ECC+CONC (25%) and CONC (14%), no change with CONT (-2%), no difference between interventions.
					Increase in lower body strength (back squat 3RM) with ECC+CONC (25%) and CONC (15%), no change with CONT (2%), no difference between interventions.
					Increase in lower body power (vertical jump; cm) with ECC+CONC (8%), no change with CONC (3%) or CONT (-1%), no difference between interventions.
Colliander and Tesch 1992 [197]	ECC+CONC n = 10, CONC n = 8, CONT n = 7, (25M); mean age: 26.6 years; training status: untrained.	KE (isokinetic; single-joint).	Volume: ECC+CONC group: 4.8 sets of 6 CONC repetitions & 6 ECC repetitions, CONC Group: 4.8 sets of 12 CONC repetitions; intensity: ECC+CONC group: ECC & CONC MVC, CONC group: CONC MVC; tempo: 60°/s.	12 weeks (3 sessions per week)	Increase in ECC KE strength (MVC) with ECC+CONC (37%) and CONC (18%), no change with CONT (NR), no difference between interventions.
					Increase in CONC KE strength (MVC) with ECC+CONC (26%) and CONC (13%), no change with CONT (NR), no difference between interventions.
					Increase in lower body strength (back squat 3RM) with ECC+CONC (23%) and CONC (13%), no change with CONT (NR), no difference between interventions.
					Increase in lower body power (vertical jump; cm) with CONC (4%), no change with ECC+CONC (8%) or CONT (NR), no difference between interventions.
Duncan et al. 1989 [212]	ECC n = 16, CONC n = 14, CONT n = 18, (48M); mean age: 23.9 years; training status: untrained.	KE (isokinetic; single-joint).	Volume: 1 set of 10 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 120°/s.	6 weeks (2 sessions per week)	Increase in ECC KE strength (MVC; 60, 120 & 180°/s) with ECC (29%), no change with CONC (7%) or CONT (-1%).
					Increase in CONC KE strength (MVC; 180°/s) with CONC (8%), no change with ECC (1%) or CONT (-5%).
Ellenbecker et al. 1988 [198]	ECC n = 11, CONC n = 11, (22F&M); mean age: NR, university students; training status: varsity tennis athletes.	ER and IR (isokinetic; single-joint).	Volume: 6 sets of 10 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: pyramid across six sets (60, 180, 210, 210, 180, 60°/s).	6 weeks (2 sessions per week)	Increase in CONC ER strength (MVC; 60, 180, 210°/s) with ECC (NR) and CONC (NR), no difference between interventions.
					Increase in CONC IR strength (MVC; 60, 180, 210°/s) with ECC (NR) and CONC (NR), no difference between interventions.
					Increase in ECC ER strength (MVC; 210°/s) with ECC (NR) and CONC (NR), no difference between interventions.
					Increase in ECC IR strength (MVC; 60 & 180°/s) with CONC (8%), no change with ECC (NR).

Elmer et al. 2012 [62]	ECC n = 6, CONC n = 6, (12M); mean age: 25.0 years; training status: untrained.	HE and KE (isokinetic cycling; multi-joint).	Volume: 21 minutes; intensity: ECC group: 30% concentric cycling peak power, CONC group: 19% concentric cycling peak power; tempo: 60rpm.	7 weeks (3 sessions per week)	Increase in leg spring stiffness (kN/m) with ECC (10%) versus CONC (-2%). Increase in jumping power (W) with ECC (7%) versus CONC (-2%).
English et al. 2014 [59]	ECC_{138} n = 8, ECC_{100} n = 8, $CONC_{66}$ n = 8, $CONC_{33}$ n = 8, CONC n = 8, (40M); mean age: 34.9 years; training status: untrained.	HE, KE and AE (isokinetic leg press; multi-joint).	Volume: 3.75 sets of 5 repetitions; intensity: ECC_{138} group: 138/76% 1RM, ECC_{100} group: 100/76% 1RM, $CONC_{66}$ group: 66/76% 1RM, $CONC_{33}$: 33/76% 1RM, CONC: 0/76% 1RM; tempo: NR.	8 weeks (3 sessions per week)	Increase in CONC HE and KE strength (leg press 1RM) with ECC_{138} (20%), ECC_{100} (13%), $CONC_{66}$ (8%), $CONC_{33}$ (8%) and CONC (8%), but ECC_{138} greater than $CONC_{66}$, $CONC_{33}$ and CONC. Increase in CONC AE strength (calf raise 1RM) with ECC_{138} (11%), ECC_{100} (12%), $CONC_{66}$ (7%) and $CONC_{33}$ (8%), no change with CONC (5%), no difference between interventions.
Farthing and Chilibeck 2003 [76]	ECC_{Fast}, $CONC_{Fast}$ n = 13, (9F, 4M), ECC_{Slow}, $CONC_{Slow}$ n = 11, (4F, 7M), CONT n = 10 (8F, 2M); mean age: 22.2 years; training status: untrained.	EF (isokinetic; single-joint).	Volume: 4.6 sets of 8 repetitions; intensity: ECC groups: ECC MVC, CONC groups: CONC MVC; tempo: fast groups: 180°/s, slow groups: 30°/s.	8 weeks (3 sessions per week)	Increase in CONC EF strength (MVC) with ECC_{Fast} (23%) greater than $CONC_{Fast}$ (1%), $CONC_{Slow}$ (6%) and CONT (0%), but not ECC_{Slow} (16%). Increase in ECC EF strength (MVC) with ECC_{Fast} (16%) greater than $CONC_{Fast}$ (-1%), ECC_{Slow} (6%), $CONC_{Slow}$ (5%) and CONT (0%).
Farthing and Chilibeck 2003 [217]	ECC_{Fast}, $CONC_{Fast}$ n = 13, (9F, 4M) ECC_{Slow}, $CONC_{Slow}$ n = 11, (4F, 7M), CONT n = 10 (8F, 2M); mean age: 22.2 years; training status: untrained.	EF (isokinetic; single-joint).	Volume: 4.6 sets of 8 repetitions; intensity: ECC groups: ECC MVC, CONC groups: CONC MVC; tempo: fast groups: 180°/s, slow groups: 30°/s.	8 weeks (3 sessions per week)	Increase in contralateral ECC EF strength (MVC; 180°/s) with ECC_{Fast} and $CONC_{Fast}$ (23%), no change with ECC_{Slow}, $CONC_{Slow}$ (-17%) or CONT (8%), no difference between interventions.
Farup et al. 2014 [199]	ECC_{Whey} and ECC n = 11, $CONC_{Whey}$ and CONC n = 11, within-subject design, (22M); mean age: 23.9 years; training status: untrained.	KE (isoinertial; single-joint).	Volume: 9.3 sets of 10.7 repetitions; intensity: ECC groups: 90/75% 1RM, CONC groups: 75% 1RM; tempo: ECC: 2s, CONC: 2s.	12 weeks (2.75 sessions per week)	Increase in CONC KE strength (MVC) with ECC (4%), $CONC_{Whey}$ (7%) and CONC (20%), no change with ECC_{Whey} (2%), no difference between interventions. Increase in ISO KE strength (MVC) with ECC_{Whey} (6%), ECC (10%), $CONC_{Whey}$ (17%) and CONC (20%), no difference between interventions. Increase in ECC KE strength (MVC) with ECC_{Whey} (10%), ECC (8%), $CONC_{Whey}$ (8%) and CONC (19%), no difference between interventions.

Franchi et al. 2014 [70]	ECC n = 6, CONC n = 6, (12M); mean age: 25.0 years; training status: untrained.	HE and KE (isokinetic; multi-joint).	Volume: 4 sets of 9 repetitions; intensity: ECC group: 80% ECC 1RM, CONC group: 80% CONC 1RM; tempo: ECC group: 3s, CONC group: 2s.	10 weeks (3 sessions per week)	Increase in ISO KE strength (MVC) with ECC (11%) and CONC (9%), no difference between interventions.
Friedmann-Bette et al. 2010 [71]	ECC n = 14, TRAD n = 11, (25M); mean age: 24.4 years; training status: strength trained.	KE (isoinertial; single-joint).	Volume: ECC group: 5 sets of 8 repetitions, TRAD group: 6 sets of 8 repetitions; intensity: ECC: 152/80% 1RM, TRAD: 80% 1RM; tempo: NR; explosive ECC and CONC.	6 weeks (3 sessions per week)	Increase in CONC KE strength (1RM) with ECC (16%) and TRAD (19%), no difference between interventions. Increase in squat jump (cm) with ECC (7%), no change with TRAD (1%).
Godard et al. 1998 [200]	ECC n = 9, TRAD n = 9, CONT n = 10, (17F, 21M); mean age: 22.4 years; training status: recreationally active.	KE (isokinetic; single-joint).	Volume: 1 set of 10 repetitions; intensity: ECC group: 120/80% 1RM, TRAD group: 80% 1RM; tempo: 30°/s.	10 weeks (2)	Increase in CONC KE strength (MVC) with ECC (81%) and TRAD (82%) versus CONT (7%), no difference between interventions.
Gross et al. 2010 [61]	ECC n = 8, TRAD n = 7 (15M); mean age: 17.6 years; training status: junior national skiers.	HE and KE (isokinetic and isoinertial; multi-joint).	Volume: ECC group: 12 sets of 30 repetitions weight training and 20 minutes ECC cycling, TRAD group: 22.5 sets of 30 repetitions; intensity: ECC group: 40% 1RM weight training and 532W ECC cycling, TRAD group: 40% 1RM; tempo: ECC cycling: 70rpm, weight training: NR.	6 weeks (3 sessions per week)	Increase in ISO HE and KE strength (leg press MVC) with ECC (10%) and TRAD (12%), no difference between interventions. Decrease in squat jump (cm) with TRAD (-4%), no change with ECC (2%). Increase in countermovement jump (cm) with ECC (7%), no change with TRAD (3%).
Hawkins et al. 1999 [201]	ECC n = 8, CONC n = 8 (within-subject design), CONT n = 12, (20F); mean age: 21.4 years; training status: untrained.	KE and KF (isokinetic; single-joint).	Volume: ECC group: 3 sets of 3 repetitions, CONC group: 3 sets of 4 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: NR.	18 weeks (3 sessions per week)	Increase in CONC KE strength (MVC) with ECC (18%) and CONC (23%), no change with CONT (-6%), no difference between interventions. Increase in ECC KE strength (MVC) with ECC (22%) and CONC (17%) increased, no change with CONT (-3%), greater increase with ECC training versus CONC. Increase in CONC KF strength (MVC) ECC (13%), no change with CONC (6%) or CONT (NR). Increase in ECC KF strength (MVC) with ECC (14%) and CONC (13%), no change with CONT (NR), no difference between interventions.
Higbie et al. 1996 [68]	ECC n = 19, CONC n = 16, CONT n = 19, (54F); mean age: 20.5 years; training status: untrained.	KE (isokinetic; single-joint).	Volume: 3 sets of 10 repetitions; intensity; ECC group: ECC MVC, CONC group: CONC MVC; tempo: 60°/s.	10 weeks (3 sessions per week)	Increase in CONC KE strength (MVC) with CONC (18%), no change with ECC (7%) or CONT (5%), greater increase with CONC training versus ECC.

					Increase in ECC KE strength (MVC) with ECC (36%) and CONC (13%), no change with CONT (-2%), greater increase with ECC training versus CONC.
					Increase in CONC KE activation (EMG) with CONC (22%) greater than CONT (-8%), no change with ECC (7%). Increase in ECC KE activation (EMG) with ECC (17%) and CONC (20%) greater than CONT (-9%), no difference between interventions.
Hortobagyi et al. 1996 [72]	ECC n = 7, CONC n = 8, CONT n = 6, (21M); mean age: 21.3 years; training status: untrained.	KE (isokinetic; single-joint).	Volume: 5.3 sets of 10 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 60°/s.	12 weeks (3 sessions per week)	Increase in CONC KE strength (MVC) with ECC (33%) and CONC (53%), no change with CONT (NR), no difference between interventions.
					Increase in ECC KE strength (MVC) with ECC (116%), no change with CONC (40%) or CONT (NR), greater increase with ECC training versus CONC.
					Increase in CONC KE activation (EMG) with CONC (28%), no change with ECC (62%) or CONT (NR), no difference between interventions.
					Increase in ECC KE activation (EMG) with ECC (188%), no change with CONC (10%) or CONT (NR), greater increase with ECC training versus CONC.
Hortobagyi et al. 1997 [218]	ECC n = 7, CONC n = 8, CONT n = 6, (21M); mean age: 21.3 years; training status: untrained.	KE (isokinetic; single-joint).	Volume: 5.3 sets of 10 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 60°/s.	12 weeks (3 sessions per week)	Increase in contralateral CONC KE Strength (MVC) with CONC (30%), no change with ECC (18%) or CONT (0%), no difference between interventions.
					Increase in contralateral ISO KE strength (MVC) with ECC (39%) and CONC (22%), no change with CONT (2%), greater increase with ECC versus CONC.
					Increase in contralateral ECC KE strength (MVC) with ECC (77%), no change with CONC (18%) or CONT (4%), greater increase with ECC versus CONC.
Hortobagyi et al. 2000 [73]	ECC n = 12, ECC+CONC n = 12, CONC n = 12, CONT n = 24, (24F, 24M); mean age: 22.0 years; training status: untrained.	KE (isokinetic; single-joint).	Volume: 5.3 sets of 10 repetitions; intensity: ECC group: ECC MVC, ECC+CONC group: ECC and CONC MVC, CONC group: CONC MVC; tempo: 60°/s.	12 weeks (3 sessions per week)	Increase in CONC KE strength (MVC) with ECC (25%), ECC+CONC (40%) and CONC (44%), no change with CONT (NR), no difference between interventions.

					Increase in ISO KE strength (MVC) with ECC (42%), ECC+CONC (38%) and CONC (31%), no change with CONT (NR), greater increase with ECC and ECC+CONC versus CONC.
					Increase in ECC KE strength (MVC) with ECC (86%), ECC+CONC (70%) and CONC (20%), no change with CONT (NR), no difference between interventions.
Kaminski et al. 1998 [202]	ECC n = 9, CONC n = 9, CONT n = 9, (27M); mean age: 22.9 years; training status: untrained.	KF (isoinertial; single-joint).	Volume: 2 sets of 8 repetitions; intensity: ECC group: 100/40% 1RM, CONC group: 80% 1RM; tempo: NR.	6 weeks (2 sessions per week)	Increase in CONC KF strength (1RM/BW) with ECC (29%) and CONC (19%), no change with CONT (5%), no difference between interventions.
					Increase in ECC KF strength (MVC) with ECC (30%), no change with CONC (13%) or CONT (-5%), no difference between interventions.
Komi and Buskirk 1972 [203]	ECC n = 11, CONC n = 10, CONT n = 10, (31M); mean age: 19.6 years; training status: untrained.	EF (isokinetic; single-joint).	Volume: 1 set of 6 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: NR.	7 weeks (4 sessions per week)	Increase in CONC EF strength (MVC) with ECC (16%) and CONC (12%) versus CONT (2%), no difference between interventions.
					Increase in ISO EF strength (MVC) with ECC (7%) versus CONT (1%), no change with CONC (6%).
					Increase in ECC EF strength (MVC) with ECC (16%) and CONC (7%) versus CONT (-4%), greater increase with ECC versus CONC.
LaStayo et al. 1999 [210]	ECC n = 4, CONC n = 5, (5F, 4M); mean age: 21.5 years; training status: untrained.	HE and KE (isokinetic cycling; multi-joint).	Volume: 27.5 minutes; intensity: ECC group: 1 L/min O_2 consumption, CONC group: 1.2 L/min O_2 consumption; tempo: 55rpm.	6 weeks (4.2 sessions per week)	Increase in ISO KE strength (MVC) with ECC (27%), no change with CONC (10%).
LaStayo et al. 2000 [211]	ECC n = 7, CONC n = 7, (14M); mean age: 23.9 years; training status: untrained.	HE and KE (isokinetic cycling; multi-joint).	Volume: 27.5 minutes; intensity: 62% maximum heart rate; tempo: 60rpm.	8 weeks (3.5 sessions per week)	Increase in ISO KE strength (MVC) with ECC (36%), no change with CONC (2%).
Liu et al. 2013 [63]	ECC+CONC$_{Fast}$ n = 10, ECC+CONC$_{Slow}$ n = 10, TRAD n = 10, (30M); mean age: 19.5 years; training status: untrained.	HE and KE (ECC groups: isokinetic, TRAD group: isoinertial; multi-	Volume: 5 sets of 10 repetitions; intensity; ECC groups: ECC MVC, TRAD group: 70% 1RM; tempo: ECC$_{Fast}$: 2.5Hz, ECC$_{Slow}$ and TRAD: 0.5Hz.	10 weeks (3 sessions per week)	Increase in lower body power (vertical jump; cm) with ECC+CONC$_{Fast}$ (4%) and ECC+CONC$_{Slow}$ (3%), no change with TRAD (2%), greater increase with ECC+CONC$_{Fast}$ versus ECC+CONC$_{Slow}$ and TRAD.

					Increase in drop jump (cm) with ECC+CONC$_{Fast}$ (6%), no change with ECC+CONC$_{Slow}$ (1%) or TRAD (1%), greater increase with ECC+CONC$_{Fast}$ versus ECC+CONC$_{Slow}$. Decrease in 30m sprint time (s) with ECC+CONC$_{Fast}$ (-0.23%), ECC+CONC$_{Slow}$ (-0.12%) and TRAD (-0.12%), greater improvement with ECC+CONC$_{Fast}$ versus ECC+CONC$_{Slow}$ and TRAD. Increase in stretch shortening cycle efficiency with ECC+CONC$_{Fast}$ (11%), no change with ECC+CONC$_{Slow}$ (4%) or TRAD (2%), greater increase with ECC+CONC$_{Fast}$ versus ECC+CONC$_{Slow}$ and TRAD.
		Joint).			
Malliaras et al. 2013 [69]	ECC$_{Heavy}$ n = 10, ECC$_{Light}$ n = 10, CONC n = 9, CONT n = 9, (38M); mean age: 27.5 years; training status: untrained.	KE (isoinertial; single-joint).	Volume: ECC$_{Heavy}$ and CONC groups: 4 sets of 7.5 repetitions, ECC$_{Light}$ group: 4 sets of 13.5 repetitions; intensity: ECC$_{Heavy}$ group: 80% ECC 1RM, ECC$_{Light}$ and CONC groups: 80% CONC 1RM; tempo: ECC: 5s, CONC: 1s.	12 weeks (3 sessions per week)	Increase in CONC KE strength (5RM) with ECC$_{Heavy}$ (77%), ECC$_{Light}$ (61%) and CONC (53%), no change with CONT (NR), greater increase with ECC$_{Heavy}$ versus ECC$_{Light}$ and CONC.
Miller et al. 2006 [204]	ECC n = 17, CONC n = 21 (38F); mean age: 20.0 years; training status: untrained.	KF and KE (isokinetic; single-joint).	Volume: 4.5 sets of 6 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 60°/s.	20 weeks (3 sessions per week)	Increase in CONC KE strength (MVC) with ECC (15%) and CONC (10%), no difference between interventions. Increase in CONC KF strength (MVC) with ECC (29%) and CONC (27%), no difference between interventions. Increase in ECC KE strength (MVC) with ECC (28%) and CONC (12%), greater increase with ECC versus CONC. Increase in ECC KF strength (MVC) with ECC (40%) and CONC (20%), greater increase with ECC versus CONC. Increase in CONC KE RFD (ms) with ECC (14%) and CONC (14%), no difference between interventions. Increase in CONC KF RFD (ms) with ECC (35%) and CONC (21%), no difference between interventions. Increase in ECC KE RFD (ms) with ECC (26%) and CONC (2%), greater increase with ECC versus CONC. Increase in ECC KF RFD (ms) with ECC (21%) and CONC (9%), greater increase with ECC versus CONC.

Mont et al. 1994 [205]	ECC n = 8, CONC n = 9, CONT n =13, (30M); mean age: 33.0 years; training status: elite tennis players.	ER and IR (isokinetic; single-joint).	Volume: 8 sets of 10 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: pyramid across eight sets (90, 120, 150, 180, 180, 180, 120, 90°/s).	6 weeks (3 sessions per week)	Increase in CONC ER strength (MVC) with ECC (9%) and CONC (7%) versus CONT (-9%), no difference between interventions.
					Increase in CONC IR strength (MVC) with ECC (2%) and CONC (12%) versus CONT (-9%), no difference between interventions.
					Increase in ECC ER strength (MVC) with ECC (18%) and CONC (10%) versus CONT (-1%), no difference between interventions.
					Increase in ECC IR strength (MVC) with ECC (5%) and CONC (18%) versus CONT (-4%), no difference between interventions.
Moore et al. 2012 [206]	ECC and CONC n = 9, within-subject design, (9M); mean age: 22.0 years; training status: untrained.	EF (isokinetic; single-joint).	Volume: ECC group 4.44 sets of 10 repetitions, CONC group: 4.44 sets of 14 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 45°/s.	9 weeks (2 sessions per week)	Increase in CONC EF strength (MVC) with ECC (11%) and CONC (14%), no difference between interventions.
					Increase in ISO EF strength (MVC) with ECC (9%) and CONC (19%), no difference between interventions.
					Increase on ECC EF strength (MVC) with ECC (8%) and CONC (11%), no difference between interventions.
Nickols-Richardson et al. 2007 [207]	ECC n = 33, CONC n = 37, (70F); mean age: 35.0 years; training status: untrained.	KF, KE, EF and EE (isokinetic; single-joint).	Volume: 4.5 sets of 6 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 60°/s.	20 weeks (3 sessions per week)	Increase in CONC KF and KE strength (MVC) with ECC (29%) and CONC (19%), no difference between interventions.
					Increase in CONC EF and EE strength (MVC) with ECC (25%) and CONC (13%), greater increase with ECC versus CONC.
Seger et al. 1998 [213]	ECC n = 5, CONC n = 5, (10M); mean age: 24.5 years; training status: moderately trained.	KE (isokinetic; single-joint).	Volume: 4 sets of 10 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 90°/s.	10 weeks (3 sessions per week)	Increase in CONC KE strength (MVC; 30 & 90°/s) with CONC (12%), no change with ECC (4%).
					Increase in ISO KE strength (MVC) with CONC (14%), no change with ECC (6%).
					Increase in ECC KE strength (MVC; 30 & 90°/s) with ECC (24%) and CONC (13%), no difference between interventions.

Spurway et al. 2000 [215]	ECC and CONC n = 20, within-subject design, (10F, 10M); mean age: 24.0 years; training status: untrained.	KE (isoinertial; single-joint).	Volume: 3 sets of 6 repetitions; intensity: ECC group: 85% ECC 1RM, CONC group: 85% CONC 1RM; tempo: NR.	6 weeks (3 sessions per week)	Increase in ECC KE strength (MVC) with ECC (26%) and CONC (23%), no difference between interventions.
Tomberlin et al. 1991 [214]	ECC n = 21, CONC n = 19, CONT n = 23, (32F, 31M); mean age: 27.1 years; training status: untrained.	KE (isokinetic; single-joint).	Volume: 3 sets of 10 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 100°/s.	6 weeks (3 sessions per week)	Increase in CONC KE strength (MVC) with CONC (8%), no change with ECC (4%) or CONT (-2%), greater increase with CONC versus ECC and CONT.
					Increase in ECC KE strength (MVC) with ECC (21%) and CONC (11%), no change with CONT (5%), greater increase with ECC versus CONC and CONT.
Vikne et al. 2006 [74]	ECC n = 9, CONC n = 8, (17M); mean age: 27.1 years; training status: resistance trained.	EF (isoinertial; single-joint).	Volume: 3.9 sets of 6 repetitions; intensity: ECC group: 94% ECC 1RM, CONC group: 94% CONC 1RM; tempo: ECC: 3.5s, CONC: explosive.	12 weeks (2.5 sessions per week)	Increase in CONC EF strength (1RM) with ECC (14%) and CONC (18%), no difference between interventions.
					Increase in ECC EF strength (1RM) with ECC (9%) and CONC (3%), greater increase with ECC versus CONC.
Yarrow et al. 2008 [208]	ECC n = 10, CONC n = 12, (22M); mean age: 22.1 years; training status: untrained.	Lower Body/Back Squat and Upper Body/Bench Press (isoinertial; multi-joint).	Volume: ECC group: 3 sets of 6 repetitions, CONC group: 4 sets of 6 repetitions; intensity: ECC group: 110/44% 1RM, CONC group: 65% 1RM; tempo: 6s per repetition.	5 weeks (3 sessions per week)	Increase in lower body strength (back squat 1RM) with ECC (19%) and CONC (25%), no difference between interventions.
					Increase in upper body strength (bench press 1RM) with ECC (9%) and CONC (10%), no difference between interventions.

Abbreviations: °/s: degrees per second, cm: centimetres, AE: ankle extensors, CONC: concentric, CONT: control, ECC: eccentric, ECC+CONC: coupled maximal eccentric and concentric contractions, EE: elbow extensors, EF: elbow flexors, EMG: electromyography, ER: shoulder external rotators, F: females, HE: hip extensors, IR: shoulder internal rotators, ISO: isometric, KE: knee extensors, KF: knee flexors, kN/m: kilonewtons per meter, L/m: litres per minute, M: males, ms: milliseconds, MVC: maximum voluntary contraction, n: number of subjects, $N \cdot s^{-1}$: newtons per second, NR: not reported, RFD: rate of force development, RM: repetition maximum, rpm: revolutions per minute, s: seconds, TRAD: traditional resistance training, W: watts.

Compared with changes in muscle strength, relatively few studies investigated changes in muscle power [61-63, 71, 196, 197] or contractile rate of force development (RFD) [204, 209]. Muscle power, as assessed primarily by lower body jump variations, increased with eccentric training within a number of studies, while concentric or traditional training had no clear effect [61-63, 196]. Furthermore, the finding of Colliander and Tesch [197] where vertical jump increased following concentric, but not eccentric, training may have been a statistically spurious observation. Closer inspection of their data indicates that eccentric training was, at least practically, superior to concentric training (i.e. 8% versus 4%; Cohen's d: 0.36). Vertical jump performance involves a SSC component and variables associated with SSC performance appear to improve to a greater extent with eccentric training. SSC efficiency (i.e. taken as the ratio of countermovement to squat jump performance), DJ performance and leg spring stiffness have been found to increase following eccentric, but not concentric or traditional resistance training [62, 63]. Squat jump performance, which involves no SSC component and therefore reflects muscle power independent of elastic energy utilization and stretch reflex potentiation, may also benefit to a greater extent following eccentric training compared with concentric or traditional resistance training [61, 71]. Aligning with observations on muscle strength, fast eccentric training appears to have a more potent effect on measures of muscle power than slow eccentric training. Vertical jump, DJ, SSC efficiency and sprinting performance (i.e. 30m) all improved to a greater extent following fast (i.e. 2.5 Hz isokinetic squat movement) combined eccentric/concentric training compared with slow combined eccentric/concentric (i.e. 0.5 Hz isokinetic squat movement) and traditional resistance training [63]. Improvements in contractile RFD appear to be dependent upon the method of assessment. Isometric RFD from 0-30ms increased to a greater extent with concentric versus eccentric training [209], while eccentric training has been found to elicit a greater increase in eccentric RFD (i.e. as inferred from time to peak torque during isokinetic knee extension and flexion) and an equivalent increase in concentric RFD compared with concentric training [204].

3.3.2.1 Muscle strength

The mechanisms underpinning strength improvements with eccentric training are likely a combination of neural, morphological and architectural factors (section 3.3.3), although relatively few studies have investigated the possible neural adaptations following eccentric training [68, 72, 203]. The mode-specificity of strength improvements in conjunction with cross-education supports the importance of neural mechanisms, while other evidence indicates that changes in eccentric strength are attained via increased agonist voluntary activation [37, 219] and decreased antagonist co-activation [220]. The inability to fully activate muscle during eccentric contractions [100], particularly in untrained subjects [36], may explain the large improvements in eccentric strength and the observation that eccentric training increases eccentric strength to a greater degree than concentric training increases concentric strength [68, 72]. In support of an improved neural drive, Vangsgaard et al. [219] found 5-weeks of eccentric training of the trapezius muscle increased muscle excitability (i.e. inferred from maximal evoked H-reflex) in concert with a 26% increase in MVC, aligning with previous findings [221]. Improvements in agonist voluntary activation during eccentric contractions may result from a disinhibition of pre-synaptic Golgi Ib and joint afferents known to inhibit excitatory muscle spindle Ia afferents [66]. EMG has been found to increase during eccentric contractions but not concentric contractions following eccentric training [68, 72], although conflicting findings have been reported [68]. Maximal EMG (i.e. peak root mean square [RMS] values and integrated voltage from the EMG [iEMG]) following training is proposed to reflect the electrical excitation of muscle, which is influenced by the number and size (i.e. type I versus type II fibres) of recruited motor units, motor unit discharge rate and synchrony [68, 72]. Based on findings using the twitch interpolation technique, motor unit activation during an isometric MVC can be, although not in all cases, maximal in untrained subjects during single joint movements [222]. It has been proposed that increases in EMG with eccentric training result from increases in motor unit discharge rate [68]. Contrary to reports on isometric contractions, maximal activation is typically inhibited during maximal eccentric contractions with untrained subjects [66], which indicates that both motor unit recruitment and discharge rates could contribute to increases in strength. The relative contribution of motor unit activation to the voluntary activation deficit may increase during compound multi-joint movements [222], but methodological limitations

with measuring motor unit activity make it challenging to corroborate this supposition. Nonetheless, it is believed that the motor unit discharge rate is the primary inhibitory mechanism constraining voluntary activation during eccentric contractions [36], and thus the neural factor which contributes most to increased eccentric strength following eccentric, or heavy, resistance training [66].

3.3.2.2 Muscle power and stretch-shortening cycle performance

Increases in muscle power following chronic resistance training are generally expected, particularly for subjects with a limited training history [223]. Muscle power is dictated by the force-velocity relationship and therefore the capacity of muscle to both produce force and shorten rapidly [191]. The neural mechanisms underpinning improvements in strength, along with morphological and architectural adaptations (Section 3.3.3), probably contribute to improvements in muscle power with eccentric training [191]. Increases in muscle power will largely arise from improvements in the capability to rapidly recruit larger motor units (i.e. type IIa and IIx) and increases in motor unit firing frequency [191]. Faster recruitment of larger motor units may be achieved by lowering the threshold of recruitment [224], or via a preferential recruitment. Experimental evidence supporting a preferential recruitment is not compelling [36], and therefore a lower threshold of recruitment seems most plausible in explaining a training-induced improvement in rapid motor unit recruitment [191]. Increases in motor unit firing frequency could also contribute to enhancements in eccentric power (i.e. during a vertical jump), and would align with the purported effects of motor unit discharge rates on eccentric strength [66]. Improvements in motor unit synchronization (i.e. intra-muscular coordination) and intermuscular co-ordination (i.e. improved synergist co-activation and decreased antagonist co-activation) could also play a role in the expression of neuromuscular power [191, 225]. Improved eccentric force control is a postulated adaptation to eccentric training [223] and it is possible that increased eccentric coordination could contribute to SSC performance. SSC performance during various outcome measures (i.e. vertical jump, DJ and SSC efficiency) can be enhanced by modulating the eccentric phase of the movement [62, 63, 65, 226]. Papadopoulos and colleagues [226] found an eccentric leg press training protocol elicited smaller changes in ankle, hip and knee angles during the eccentric phase of a DJ which corresponded to

improved jump height, power and contact time. The increased joint stiffness during the eccentric phase of the SSC probably enhanced the utilization of elastic energy [226] and allowed the muscle to operate closer to its optimum length and shortening velocity [65]. These adaptations appear to translate to functional performance such as sprinting, particularly with inclusion of fast mixed eccentric/concentric contractions in the training protocol [63]. Cook et al. [64] found that 3-weeks of controlled tempo eccentric training in semi-professional Rugby players improved back squat, bench press and countermovement jump performance to a greater extent than traditional resistance training. However the authors found that the addition of overspeed sprint and power training was necessary to elicit increases in 40m sprint performance with eccentric training [64]. A 3.3% increase in flying 10m sprint time has also been reported in well trained soccer players following 10-weeks of eccentric flywheel training [227], but contraction speed was not reported. While further research is necessary, it may be postulated that fast contraction velocities optimize the transfer of eccentric-related adaptations to sprint performance involving a fast SSC component.

3.3.2.3 Contractile rate of force development

The lack of studies investigating the effects of eccentric training on RFD combined with divergent methods of assessment make it difficult to draw firm conclusions in this area. Contractile RFD is influenced by muscle strength, CSA, fibre type and MHC composition, MTU viscoelastic properties, and neural drive [228, 229]. The relative contribution of these factors probably depends upon the RFD time interval assessed. A combination of neural drive and intrinsic muscle properties (i.e. MHC composition) appears to play a marked role during early phase (i.e. < 100 ms) RFD [230] which is unsurprising given the cross-bridge cycling rates of both IIx and IIa fibres are substantially greater than type I fibres [231, 232]. Improvements in late phase (i.e. > 100 ms) RFD may be more related to neural drive, muscle CSA and tendon/aponeurosis stiffness [230]. Indeed, Andersen and Aagaard [229] found that very early RFD (i.e. < 40 ms) was related to twitch RFD more so than maximal strength, and from 90 ms onwards strength accounted for 52-81% of the variance in voluntary RFD. Furthermore, tendon and aponeurosis stiffness has been demonstrated to account for up to 30% of the variance in RFD from 0-200 ms [228]. Training interventions which change these

underlying mechanisms could plausibly influence early and late phase RFD to differing extents [233]. Six weeks of fast concentric (i.e. 180°/s) training can improve early phase RFD by 33-56% independent of any change in late phase RFD or strength, a finding which has been attributed to changes in neural drive [234]. Fast eccentric (i.e. 180°/s) resistance training has been similarly demonstrated to improve early phase RFD by 30%, but also in conjunction with a 28% improvement in strength [230]. The mechanisms by which eccentric training improve early phase RFD may be a combination of intrinsic muscle and neural adaptations. Similar to improvements in muscle strength and power, the unique neural strategies involved with eccentric training may improve RFD via both increased volitional supraspinal drive and spinal reflex disinhibition [230]. Late phase improvements in RFD have been demonstrated to occur in parallel with improvements in strength with heavy resistance training [229], and therefore the increases in strength observed with eccentric training may contribute to enhanced late-phase RFD. Isometric training which includes the intention to contract explosively (i.e. "ballistic-intended") has been found to improve both early and late RFD [235], and it has been proposed that the intention to act explosively is more important than the type of contraction performed [234]. Further research is necessary to determine best practice in maximising improvements in RFD; as long as there is maximal intent to contract explosively, eccentric, isometric and concentric training protocols can lead to performance enhancements.

3.3.2.4 Summary of eccentric training effects on muscle mechanical function

In summary, eccentric training may improve overall strength to a greater extent than concentric and traditional modalities, although there is a mode-specificity (i.e. contraction type and velocity) of improvements [67]. Increases in strength result from a combination of neural, morphological and architectural adaptations. Increased voluntary activation of agonists during eccentric contractions via a disinhibition of excitatory inflow to spinal motor neurons may underpin the marked increases in eccentric strength observed following training [66]. Based on EMG experiments an increase in motor unit discharge rate appears to play a more important role than changes in motor unit recruitment [68], although further research is necessary to determine whether this observation holds during compound, multi-joint movements [222]. Eccentric training

improves muscle power and SSC performance to a greater extent than concentric or traditional modalities, while reports on changes in RFD have been mixed. Improvements are likely related to increases in eccentric and concentric strength, an improved ability to rapidly recruit fast motor units, a shift towards a faster muscle phenotype (section 3.3.3), and an enhanced eccentric phase within the SSC. Given the mode-specificity of adaptations, dedicated concentric training should be performed in addition to eccentric training if improvements in concentric strength, and possibly power, are of importance. In practice, traditional resistance training combining eccentric and concentric actions remains most prevalent. The use of traditional exercises with additional overload above the concentric maximum during the eccentric phase may therefore maximise outcomes across concentric, isometric and eccentric strength [59]. Furthermore, fast eccentric velocities may induce greater strength, power and SSC improvements than slow eccentric velocities [63, 76]. It has also been suggested that the optimal duration between the cessation of eccentric training and performance assessment may necessarily differ from concentric training in expressing improvements in muscle mechanical function [236]. More research is needed to determine the fatigue, recovery and adaptation time-course, and subsequent performance responses, with eccentric training.

3.3.3 Muscle-tendon unit morphology and architecture

Eccentric [59, 61, 68, 70, 71, 74, 76, 194, 196, 200, 201, 206, 211, 213, 237, 238], concentric [70, 76, 194, 196, 206, 207, 237, 238] and traditional [68, 71, 200] resistance training have all been found to increase muscle size using a variety of measures (i.e. dual-energy X-ray absorptiometry [DXA], muscle circumference, magnetic resonance imaging [MRI], peripheral computerised tomography [pQCT] and ultrasound) (Table 3.2). Muscle hypertrophy is a common finding with eccentric and concentric training modalities. Either a greater increase [59, 61, 68, 76, 201, 211, 213], or no difference [70, 194, 196, 206, 207, 237, 238], has been reported following eccentric training. Those comparing eccentric training with traditional resistance training reported no differences between modalities [71, 200]. Contraction type appears to mediate a region specific hypertrophy; eccentric training tends to induce greater increases in distal muscle size, while mid-muscle hypertrophy occurs to a greater extent following

concentric training [70, 213]. It is plausible that reported literature is not entirely representative of the extent of adaptation with eccentric training given that muscle morphology and architecture are typically assessed at the mid-belly of the muscle. When looking at fibre type specific responses (i.e. via muscle biopsy and electron microscopy), greater increases in type II fibre area have been observed with eccentric versus concentric or traditional training [71-74]. In particular, an improved maintenance of, or increase, in type IIx fibre area has been reported with eccentric training relative to concentric [196], or traditional resistance training [71, 73]. Fibre type composition may be uniquely influenced by eccentric training and either an improved maintenance of [74, 196], or similar reduction [72], of IIx fibres has been found compared with concentric training. As per changes in muscle strength, the intensity and velocity of muscle contraction influence the magnitude of muscle hypertrophy with eccentric training. Even when all conditions involve supra-maximal loads (i.e. greater than maximal concentric strength), greater increases in hypertrophy have been found with heavier eccentric training conditions [59], while fast eccentric velocities (i.e. 180°/s) also induced larger increases in muscle CSA [76]. The addition of whey protein hydrolysate supplementation in the post-exercise period has been found to increase [238], or have no effect on [237], the hypertrophic response following eccentric training. Few studies investigated changes in muscle architecture [70, 194], or tendon structure and function [69, 237] with differing contraction types. Vastus lateralis fascicle length was found to increase with both eccentric and concentric training [194], or eccentric training only [70]. Conflicting results were reported for vastus lateralis fascicle angle with increases observed following eccentric training only [194], or concentric training only [70]. Patellar tendon CSA can increase with eccentric training, while the addition of whey protein hydrolysate supplementation appears necessary to promote increases with concentric training [237]. Patellar tendon Young's modulus at 50-75% MVC has been demonstrated to increase with both eccentric and concentric training, but only with eccentric training at 75-100% MVC [69]. Maximal tendon force and stress also increased with eccentric but not concentric training; furthermore, a particularly marked increase was observed with heavier eccentric loading [69].

Table 3.2. Studies comparing the effects of eccentric-overload (ECC) and coupled maximal eccentric and concentric contractions (ECC+CONC) with traditional (TRAD) and concentric-only (CONC) resistance training on muscle tendon unit (MTU) morphology and architecture.

Study	Population	Muscle groups (modality)	Intervention	Training duration	Training effect ($p < 0.05$)
Blazevich et al. 2007 [194]	ECC n = 11, CONC n = 10, CONT n = 9, (16F, 14M); mean age: 22.8 years; training status: untrained.	KE (isokinetic; single-joint)	Volume: 5 sets of 6 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 30°/s.	10 weeks (3 sessions per week)	Increase in quadriceps CSA (cm^3) with ECC and CONC (average change: 10%), no change with CONT (NR), no difference between conditions.
					Increase in quadriceps fascicle length (mm) with ECC (3%) and CONC (6%), no change with CONT (NR), no difference between conditions.
					Increase in vastus lateralis fascicle angle (°) with ECC (21%), no change with CONC (13%) or CONT (NR), no difference between interventions.
Colliander and Tesch 1990 [196]	ECC+CONC n = 11, CONC n = 11, CONT n = 7, (29M); mean age: 26.3 years; training status: untrained.	KE (isokinetic; single-joint)	Volume: 4.8 sets of 12 repetitions; intensity: ECC+CONC group: ECC & CONC MVC, CONC group: CONC MVC; tempo: 60°/s.	12 weeks (3 sessions per week)	Increase in thigh CSA (mm) with ECC+CONC (1%) and CONC (1%), no change with CONT (0.2%), no difference between interventions.
					Decrease in quadriceps type IIx area (μm^2) with CONC (-30%), no change with ECC+CONC (-34%) or CONT (-33%), no difference between interventions.
					Decrease in quadriceps type IIx fibre composition (%) with CONC (-43%), no change with ECC+CONC (-49%) or CONT (-75%), no difference between interventions.
English, 2014 [59]	ECC_{138} n = 8, ECC_{100} n = 8, $CONC_{66}$ n = 8, $CONC_{33}$ n = 8, CONC n = 8, (40M); mean age: 34.9 years; training status: untrained.	HE, KE and AE (isokinetic leg press; multi-joint)	Volume: 3.75 sets of 5 repetitions; intensity: ECC_{138} group: 138/76% 1RM, ECC_{100} group: 100/76% 1RM, $CONC_{66}$ group: 66/76% 1RM, $CONC_{33}$: 33/76% 1RM, CONC: 0/76% 1RM; tempo: NR.	8 weeks (3 sessions per week)	Increase in leg CSA (kg) with ECC_{138} (2.4%), no change with ECC_{100} (1.5%), $CONC_{66}$ (2.2%), $CONC_{33}$ (1.5%) or CONC (-1.5%), no difference between conditions.
Farthing and Chilibeck 2003 [76]	ECC_{Fast}, $CONC_{Fast}$ n = 13, (9F, 4M) ECC_{Slow}, $CONC_{Slow}$ n = 11, (4F, 7M), CONT n = 10 (8F, 2M); mean age: 22.2 years; training status: untrained.	EF (isokinetic; single-joint)	Volume: 4.6 sets of 8 repetitions; intensity: ECC groups: ECC MVC, CONC groups: CONC MVC; tempo: Fast groups: 180°/s, Slow groups: 30°/s.	8 weeks (3 sessions per week)	Increase in biceps CSA (mm) with ECC_{Fast} (13%), $CONC_{Fast}$ (3%), ECC_{Slow} (8%), $CONC_{Slow}$ (5%), no change with CONT (-1%), greater increase with ECC_{Fast} versus $CONC_{Fast}$, $CONC_{Slow}$ and CONT.

Farup et al. 2014 [199]	ECC$_{Whey}$ and ECC n = 11, CONC$_{Whey}$ and CONC n = 11, within-subject design, (22M); mean age: 23.9 years; training status: untrained.	KE (isoinertial; single-joint)	Volume: 9.3 sets of 10.7 repetitions; intensity: ECC groups: 90/75% 1RM, CONC groups: 75% 1RM; tempo: ECC: 2s, CONC: 2s.	12 weeks (2.75 sessions per week)	Increase in quadriceps type I fibre CSA (μm^2) with ECC$_{Whey}$ (14%), ECC (16%), CONC$_{Whey}$ (22%) and CONC (12%), no difference between interventions. Increase in quadriceps type II fibre CSA (μm^2) with CONC$_{Whey}$ (25%), no change for ECC$_{Whey}$ (1%), ECC (11%) or CONC (7%), greater increase with CONC$_{Whey}$ versus ECC$_{Whey}$ and CONC.
Farup et al. 2014 [237]	ECC$_{Whey}$ and ECC n = 11, CONC$_{Whey}$ and CONC n = 11, within-subject design, (22M); mean age: 23.9 years; training status: untrained.	KE (isoinertial; single-joint)	Volume: 9.3 sets of 10.7 repetitions; intensity: ECC groups: 90/75% 1RM, CONC groups: 75% 1RM; tempo: ECC: 2s, CONC: 2s.	12 weeks (2.75 sessions per week)	Increase in quadriceps CSA (cm^2) with ECC$_{Whey}$ (6%), ECC (2%), CONC$_{Whey}$ (5%) and CONC (3%), no difference between interventions. Increase in patellar tendon CSA (cm^2) with ECC$_{Whey}$ (15%), ECC (10%) and CONC$_{Whey}$ (15%), no change with CONC (7%), no difference between interventions.
Franchi et al. 2014 [70]	ECC n = 6, CONC n = 6, (12M); mean age: 25.0 years; training status: untrained.	HE and KE (isokinetic; multi-joint)	Volume: 4 sets of 9 repetitions; intensity: ECC group: 80% ECC 1RM, CONC group: 80% CONC 1RM; tempo: ECC group: 3s, CONC group: 2s.	10 weeks (3 sessions per week)	Increase in quadriceps CSA (cm^3) with ECC (6%) and CONC (8%), no difference between interventions. Increase in quadriceps fascicle length (cm) with ECC (12%) and CONC (5%), greater increase with ECC versus CONC. Increase in vastus lateralis fascicle angle (°) with CONC (30%), no change with ECC (5%), greater increase with CONC versus ECC.
Friedmann-Bette et al. 2010 [71]	ECC n = 14, TRAD n = 11, (25M); mean age: 24.4 years; training status: strength trained.	KE (isoinertial; single-joint)	Volume: ECC group: 5 sets of 8 repetitions, TRAD group: 6 sets of 8 repetitions; intensity: ECC: 152/80% 1RM, TRAD: 80% 1RM; tempo: NR; explosive ECC and CONC.	6 weeks (3 sessions per week)	Increase in quadriceps CSA (cm^2) with ECC (6%) and TRAD (8%), no difference between interventions. Increase in quadriceps type IIx fibre CSA (μm^2) with ECC (20%), no change with TRAD (10%), no difference between interventions.

Godard et al. 1998 [200]	ECC n = 9, TRAD n = 9, CONT n = 10, (12F, 16M); mean age: 22.4 years; training status: recreationally active.	KE (isokinetic; single-joint)	Volume: 1 set of 10 repetitions; intensity: ECC group: 120/80% 1RM, TRAD group: 80% 1RM; tempo: 30°/s.	10 weeks (2 sessions per week)	Increase in thigh CSA (mm) with ECC (5%) and TRAD (6%) versus CONT (1%), no difference between interventions.
Gross et al. 2010 [61]	ECC n = 8, TRAD n = 7 (15M); mean age: 17.6 years; training status: junior national skiers.	HE and KE (isokinetic and isoinertial; multi-joint)	Volume: ECC group: 12 sets of 30 repetitions weight training and 20 minutes ECC cycling, TRAD group: 22.5 sets of 30 repetitions; intensity: ECC group: 40% 1RM weight training and 532W ECC cycling, TRAD group: 40% 1RM; tempo: ECC cycling: 70rpm, weight training: NR.	6 weeks (3 sessions per week)	Increase in leg lean mass (g) with ECC (2%), no change with TRAD (NR), no difference between interventions.
Hawkins et al. 1999 [201]	ECC n = 8, CONC n = 8 (within-subject design), CONT n = 12, (20F); mean age: 21.4 years; training status: untrained.	KF and KE (isokinetic; single-joint)	Volume: ECC group: 3 sets of 3 repetitions, CONC group: 3 sets of 4 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: NR.	18 weeks (3 sessions per week)	Increase in leg lean mass (g) with ECC (4%), no change with CONC (2%) or CONT (1%), no difference between interventions.
Higbie et al. 1996 [68]	ECC n = 19, CONC n = 16, CONT n = 19, (54F); mean age: 20.5 years; training status: untrained.	KE (isokinetic; single-joint)	Volume: 3 sets of 10 repetitions; intensity; ECC group: ECC MVC, CONC group: CONC MVC; tempo: 60°/s.	10 weeks (3 sessions per week)	Increase in quadriceps CSA (cm^2) with ECC (7%) and CONC (5%), no change with CONT (-1%), greater increase with ECC versus CONC.
Hortobagyi et al. 1996 [72]	ECC n = 7, CONC n = 8, CONT n = 6, (21M); mean age: 21.3 years; training status: untrained.	KE (isokinetic; single-joint)	Volume: 5.3 sets of 10 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 60°/s.	12 weeks (3 sessions per week)	Increase in quadriceps type II fibre CSA (μm^2) with ECC (38%), no change with CONC (3%) or CONT (NR), greater increase with ECC versus CONC.
					Increase in quadriceps type IIa fibre composition (%) with ECC (31%) and CONC (22%), no change with CONT (NR), no difference between interventions.
					Decrease in quadriceps Type IIx fibre composition (%) with ECC (-48%) and CONC (-60%), no change with CONT (NR), no difference between interventions.

Hortobagyi et al. 2000 [73]	ECC n = 12, ECC+CONC n = 12, CONC n = 12, CONT n = 24, (24F, 24M); mean age: 22.0 years; training status: untrained.	KE (isokinetic; single-joint)	Volume: 5.3 sets of 10 repetitions; intensity: ECC group: ECC MVC, ECC+CONC group: ECC and CONC MVC, CONC group: CONC MVC; tempo: 60°/s.	12 weeks (3 sessions per week)	Increase in quadriceps type I fibre CSA (μm^2) with ECC (10%), ECC+CONC (11%) and CONC (4%), no change with CONT (NR), no difference between interventions.
					Increase in quadriceps type IIa fibre CSA (μm^2) with ECC (16%), ECC+CONC (9%) and CONC (5%), no change with CONT (NR), greater increase with ECC and ECC+CONC versus CONC.
					Increase in quadriceps type IIx fibre CSA (μm^2) with ECC (16%), ECC+CONC (10%) and CONC (5%), no change with CONT (NR), greater increase with ECC versus ECC+CONC and CONC.
LaStayo et al. 2000 [211]	ECC n = 7, CONC n = 7, (14M); mean age: 23.9 years; training status: untrained.	HE and KE (isokinetic cycling; multi-joint)	Volume: 27.5 minutes; intensity: 62% maximum heart rate; tempo: 60rpm.	8 weeks (3.5 sessions per week)	Increase in quadriceps muscle fibre CSA (μm^2) with ECC (52%), no change with CONC (11%), no difference between interventions.
Malliaras et al. 2013 [69]	ECC_{Heavy} n = 10, ECC_{Light} n = 10, CONC n = 9, CONT n = 9, (38M); mean age: 27.5 years; training status: untrained.	KE (isoinertial; single-joint)	Volume: ECC_{Heavy} and CONC groups: 4 sets of 7.5 repetitions, ECC_{Light} group: 4 sets of 13.5 repetitions; intensity: ECC_{Heavy} group: 80% ECC 1RM, ECC_{Light} and CONC groups: 80% CONC 1RM; tempo: ECC: 5s, CONC: 1s.	12 weeks (3 sessions per week)	Increase in patellar tendon young's modulus (MPa; 50-75%) with ECC_{Heavy} (87%), ECC_{Light} (59%) and CONC (81%) versus CONT (-3%), no difference between interventions.
					Increase in patellar tendon young's modulus (MPa; 75-100%) with ECC_{Heavy} (84%) versus CONT (3%), no change with ECC_{Light} (59%) or CONC (71%), no difference between interventions.
					Increase in tendon force (N) with ECC_{Heavy} (31%) and ECC_{Light} (16%), no change with CONC (18%) or CONT (4%), ECC_{Heavy} greater than CONT, no difference between interventions.
					Increase in tendon stress (%) with ECC_{Heavy} (24%), no change with ECC_{Light} (13%), CONC (14%) or CONT (2%), no difference between interventions.

Moore et al. 2012 [206]	ECC and CONC n = 9, within-subject design, (9M); mean age: 22.0 years; training status: untrained.	EF (isokinetic; single-joint)	Volume: ECC group 4.44 sets of 10 repetitions, CONC group: 4.44 sets of 14 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 45°/s.	9 weeks (2 sessions per week)	Increase in biceps CSA (nm^2) with ECC (7%) and CONC (5%), no difference between interventions.
Nickols-Richardson et al. 2007 [207]	ECC n = 33, CONC n = 37, (70F); mean age: 35.0 years; training status: untrained.	KF, KE, EF and EE (isokinetic; single-joint)	Volume: 4.5 sets of 6 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 60°/s.	20 weeks (3 sessions per week)	Increase in lean body mass (kg) with ECC (2%) and CONC (2%), no difference between interventions.
Rahbek et al. 2014 [238]	ECC$_{Whey}$ and ECC n = 12, CONC$_{Whey}$ and CONC n = 12, within-subject design, (24M); mean age: 23.9 years; training status: untrained.	KE (isoinertial; single-joint)	Volume: 9.3 sets of 10.7 repetitions; intensity: ECC groups: 90/75% 1RM, CONC groups: 75% 1RM; tempo: ECC: 2s, CONC: 2s.	12 weeks (2.75 sessions per week)	Increase in quadriceps CSA (cm^2) with ECC$_{Whey}$ (8%), ECC (3%), CONC$_{Whey}$ (6%) and CONC (4%), greater increase with ECC$_{Whey}$ and CONC$_{Whey}$ versus ECC and CONC.
Seger et al. 1998 [213]	ECC n = 5, CONC n = 5, (10M); mean age: 24.5 years; training status: moderately trained.	KE (isokinetic; single-joint)	Volume: 4 sets of 10 repetitions; intensity: ECC group: ECC MVC, CONC group: CONC MVC; tempo: 90°/s.	10 weeks (3 sessions per week)	Increase in quadriceps CSA (cm^2) with ECC (4%), no change with CONC (3%), no difference between interventions.
Vikne et al. 2006 [74]	ECC n = 9, CONC n = 8, (17M); mean age: 27.1 years; training status: resistance trained.	EF (isoinertial; single-joint)	Volume: 3.9 sets of 6 repetitions; intensity: ECC group: 94% ECC 1RM, CONC group: 94% CONC 1RM; tempo: ECC: 3.5s, CONC: explosive.	12 weeks (2.5 sessions per week)	Increase in biceps CSA (cm^2) with ECC (11%), no change with CONC (3%), greater increase with ECC versus CONC.
					Decrease in biceps type I fibre CSA (μm^2) with ECC (-9%), no change with CONC (-1%), no difference between interventions.
					Increase in biceps type II fibre CSA (μm^2) with ECC (9%), no change with CONC (1%), no difference between interventions.
					Decrease in biceps type IIx fibre composition (%) with CONC (-3%), no change with ECC (1%), no difference between interventions.

Abbreviations: °/s: degrees per second, μm: micrometre, cm: centimetres, CONC: concentric, CONT: control, CSA: cross-sectional area, ECC: eccentric, ECC+CONC: coupled maximal eccentric and concentric contractions, F: females, kg, kilograms, M: males, mm: millimetres, MPa: megapascal, ms: milliseconds, MVC: maximum voluntary contraction, n: number of subjects, N: newtons, $N \cdot s^{-1}$: newtons per second, NR: not reported, RM: repetition maximum, rpm: revolutions per minute, s: seconds, TRAD: traditional resistance training, W: watts.

3.3.3.1 Muscle CSA and architecture

Increased muscle CSA is generally expected following a resistance training intervention of sufficient duration and is directly related to an increase in workload and tension development [76]. The number of muscle fibres does not appear to increase during post-natal growth or as a result of training in humans [239]. However, the CSA of existing fibres does increase considerably (i.e. via increased myofibril content) in response to mechanical loading [239]. Muscle hypertrophy with heavy resistance training is a product of increased protein translation, upregulation of genes involved in anabolic mechanisms, and satellite cell activation/proliferation [71, 239]. The conversion of a mechanical signal (i.e. generated during contraction) to a molecular event involves the upregulation of primary and secondary messengers within a signalling cascade to activate and/or repress pathways which regulate gene expression and protein synthesis/degradation [240]. Proteins are constantly being synthesized and broken down, even in adult muscle, therefore protein accumulation results from an increased rate of proteins being synthesized and a decreased rate of protein degradation [239]. Three factors are believed to mediate the hypertrophic signalling response to training; mechanical tension, muscle damage (i.e. EIMD) and metabolic stress [241]. The apparent superiority of eccentric training [67], or at least the inclusion of eccentric contractions (i.e. traditional training), may therefore be due to higher levels of both mechanical tension and EIMD than concentric training [52]. High levels of tension induce a mechanochemical signal to upregulate anabolic molecular and cellular activity within myofibres and satellite cells; the combined effects of active tension from contractile elements and passive tension (i.e. stretch induced strain) from collagen content within the extracellular matrix and titin are believed to induce a more potent signal for protein synthesis [147]. Indeed, stretch-induced strain from eccentric contractions, sensed within the Z-line region of titin [242], appears to elicit a specific anabolic signalling response [240, 243]. Chronic stretch of muscle *per se* upregulates protein synthesis and increases the number of sarcomeres in series [239]. These observations may explain not only the increases in CSA, but also the increases in fascicle length with eccentric training [54, 70, 194, 244-247].

Franchi and colleagues [70] postulated that increased distal muscle hypertrophy with eccentric training reflects an increased CSA via sarcomeres in series in contrast to the

addition of sarcomeres in parallel with concentric training. This mechanism would also explain the increased fascicle angle with concentric training [70], although increases in fascicle angle have also been reported following eccentric training [194, 236, 246, 247], and it is likely that these adaptations can occur in concert to varying degrees. It is not entirely clear which mechanisms instigate the hypertrophic response in the presence of EIMD and increases in muscle size can still occur in the absence of muscle damage [248].

Nonetheless, it is posited as an additive factor with eccentric training. The acute inflammatory response associated with eccentric contractions and EIMD is believed to induce a release of growth factors which regulate satellite cell activation/proliferation and anabolic signalling [241]. Increased cytokine activity (i.e. monocyte chemotactic protein-1 [MCP-1] and interferon gamma-induced protein 10 [IP-10]) has been reported following eccentric, but not concentric, exercise [49]. IP-10 within skeletal muscle is postulated to recruit T lymphocytes [49, 249], and T cell infiltration has been found to enhance satellite cell activation and muscle regeneration in mice [250]. Both heavier eccentric loading and fast eccentric contractions involve high levels of tension generation per active motor unit [43, 114], and influence the magnitude of EIMD [156, 157] which may explain the enhanced hypertrophic response when these two variables are emphasised [59, 76, 77]. A greater resistance to fatigue has been observed across a series of maximal contractions [48], and it is probable that metabolic stress will be lower during eccentric versus concentric training [251]. Interestingly, the utilization of extended duration eccentric cycling (i.e. 20-30 minutes) of a relatively low contraction intensity per repetition has been demonstrated to lead to increases in muscle CSA [61, 211]. It is possible that under these conditions that there is a progressive recruitment and fatigue of higher threshold motor units which in turn can instigate a marked hypertrophic response independent of high levels of mechanical tension [252]. Therefore, the inclusion of concentric contractions (i.e. traditional resistance training), eccentric contractions to fatigue, or a combination of eccentric loading and blood flow restriction [253], may be warranted if maximal hypertrophy is the objective.

3.3.3.2 *Muscle fibre size and composition*

Greater hypertrophy in type II muscle fibres compared with type I muscle fibres is not uncommon with resistance training [254]. Fast contracting fibres are recruited infrequently and their selective hypertrophy is proposed to be an adaptive response to aid power development during periods of near-maximal recruitment [239]. A greater increase in type II fibre area when comparing eccentric with concentric training may reflect the overall greater increase in muscle CSA. It has been further suggested that an increased recruitment, tension generating capacity and predisposition to damage of fast twitch fibres [54] contribute to the propensity for type IIa [72, 77], and IIx [71, 77] fibre hypertrophy with eccentric training. Eccentric training appears to exert a unique influence upon the MHC phenotype shift with either improved maintenance of [74, 196, 255], or increase in [75], in IIx fibre composition following training. A shift in fibre type composition (i.e. MHC isoform), and particularly a shift from MHC IIx to IIa is commonly reported following resistance training [72, 74, 256], which can be subsequently reversed, or overshoot above pre-existing levels, with detraining [257]. Increased muscle activity via either endurance or traditional resistance exercise appears to switch off the IIx gene in IIx fibres, thus increasing the proportion of IIa fibres at the expense of IIx fibres [256]. It is proposed that both the total number of contractions (i.e. nerve impulses) and maximal tensile load exerted on muscle mediate the MHC shift [256]. The MHC IIx reduction and subsequent overshoot phenomena are not well understood, but it has been postulated that IIx is the 'default' MHC gene [256, 258], and training appears to induce a shift towards a more fatigue-resistant phenotype [257]. Multiple lines of evidence are suggestive of a specific response with eccentric contractions. Friedmann-Bette and colleagues (2010) found an increase in IIa *in situ* hybridisations, or fibres expressing elevated levels of IIx messenger RNA (mRNA), which were postulated to be in transition [71] and a tendency towards an increase in IIx mRNA has also been reported following a submaximal eccentric training protocol [259]. While changes in fibre type and MHC mRNA do not always occur in parallel, long-term steady state levels of mRNA are reasonably well correlated with muscle fibre composition [259]. Furthermore, a 10-week, fast (i.e. 180°/s), isokinetic eccentric training intervention of the elbow flexors was demonstrated to increase type IIx composition by 7% [75]. These chronic findings align with observations of acute satellite cell [55] and anabolic signalling pathway upregulation [56] in type II fibres

following eccentric exercise, and support the proposition of a shift towards a faster phenotype with eccentric training [2].

3.3.3.3 Tendon CSA and qualitative properties

Historically, tendon tissue was considered inert, relatively nonvascular and inelastic. However, recent research has highlighted the dynamic nature of the extracellular matrix and thus adaptive capacity in response to mechanical load [260]. Changes in tendon structure and function appear to be partly mediated by contraction type [69]. Unfortunately, few studies have compared the effects of eccentric training with other resistance training modalities on tendon adaptation. Eccentric loading has gained widespread implementation within the rehabilitation setting as a tool to manage lower limb tendinopathy and improve tendon structure [260, 261]. However, the mechanisms underpinning the improvements with eccentric loading are not well understood [69]. Chronic loading has been demonstrated to increase tendon stiffness, and possibly CSA, and it seems maximising tendon strain may be necessary in optimizing the adaptive response [69, 247, 262]. In one investigation comparing heavy eccentric, light eccentric and concentric training, only heavy eccentric loading elicited improvements in patellar tendon Young's modulus (75-100% MVC) and strain (%) without concomitant increases in tendon CSA [69], aligning with a previous report of heavy eccentric training inducing a reduction in elbow flexor series elastic component compliance [263]. In contrast to these findings, a decrease [264], or no change [260], in Achilles tendon stiffness has been reported following the implementation of a popular submaximal eccentric heel drop protocol [265]. These observations may be related to the contraction intensity and thus provide further support for the importance of load for increasing tendon stiffness. Changes in tendon stiffness in the absence of increases in CSA may be due to increased collagen packing density, alterations in crimp angle or increased water content [69, 266]. As tendon is metabolically active [264, 266], adaptation may be driven by changes in rates of protein synthesis and degradation similar to muscle tissue in a coordinated musculo-tendinous response [267]. The cellular tensegrity model proposes that cells (i.e. myofibres and fibroblasts) can respond in a coordinated fashion to mechanical stress via integrins located in the plasma membrane and proteins connecting the extracellular matrix to the cytoskeleton which

stimulates functional remodelling of the MTU [267]. The magnitude of mechanical stress may augment the signalling response and thus explain the greater adaptation with heavy versus light eccentric training [69]. The finding that eccentric training can increase tendon CSA [237] is of interest as other acute interventions seem to be less effective at eliciting quantitative changes in tendon tissue. Plyometric training [268], and traditional resistance training [269], have been found to increase Achilles tendon stiffness but not CSA. Long term endurance training is associated with increased Achilles tendon CSA [270] which suggests that long term chronic loading may be necessary to elicit quantitative changes in tendon with submaximal loads. It appears that heavy eccentric training can induce both qualitative and quantitative changes in tendon, although more research is necessary to clarify the optimal loading conditions.

3.3.3.4 Summary of eccentric training effects on MTU morphology and architecture

Eccentric training appears to elicit greater increases in muscle CSA than concentric or traditional resistance training. The combination of heavier absolute loads and a smaller number of recruited motor units during eccentric training [36] involves high levels of mechanical tension per motor unit [114] and a greater propensity for EIMD [178]. These factors, combined with stretch-induced strain [147], may stimulate the hypertrophic signalling response to a greater extent than concentric or traditional resistance training [241]. Heavy eccentric loads and fast contraction velocities both appear to further stimulate the adaptive response [59, 75-77]. The pattern of increased muscle CSA appears to be mediated by contraction type and eccentric training may promote the addition of sarcomeres in series, as inferred from changes in muscle fascicle length [70, 194]. Selective increases in fast twitch fibre size have been reported and there is evidence to suggest that a shift towards a fast phenotype can occur as a result of chronic eccentric training [6]. The predisposition for fast twitch fibre hypertrophy probably results from an increased recruitment with heavy loads, the tension generating capacity and subsequent damage of these fibres [71, 72]. While further research is required, it is possible an upregulation of IIx mRNA signalling can occur with eccentric training [71, 259], leading to an attenuated IIx to IIa shift [74, 196, 255], or an increase in IIx composition with fast contractions [75]. Eccentric training may promote increases in tendon stiffness [69] and CSA [237] which influence the

storage and return of elastic strain energy and probably contribute to the observed enhancements in SSC performance. The MTU morphological and architectural adaptations, in conjunction with changes in muscle mechanical function (section 3.3.2), have important implications for strength, power and speed performance; however, more research is necessary to determine how these findings translate to trained athletes.

3.4 Conclusion

Eccentric training using external loads greater than the relative concentric training intensity is a potent stimulus for enhancements in muscle mechanical function, MTU morphological, and architectural adaptations. The inclusion of eccentric loads above maximal concentric strength is therefore an avenue to induce novel training stimuli and effect change in key determinants, and functional metrics, of strength, power and speed performance. Strength improvements are largely mode specific and arise from a combination of neural, morphological and architectural adaptations [67]. Increased agonist volitional drive is posited as the primary contributing factor to the marked increases in eccentric strength observed following training [66]. Eccentric training improves concentric muscle power and SSC performance to a greater extent than concentric or traditional modalities [61-63, 196]. Reports on changes in RFD have been mixed [204, 209], although limited research in this area has been undertaken. Improvements in muscle power and SSC performance are likely related to improvements in total strength, an improved ability to rapidly recruit fast motor units, qualitative changes to tendon tissue and an enhanced eccentric phase within the SSC [191]. Eccentric training can elicit greater increases in muscle CSA than concentric or traditional resistance training. High levels of mechanical tension per active motor unit [114], stretch-induced strain [147], and a greater propensity for EIMD [178] with eccentric training may stimulate anabolic signalling to a greater extent than concentric or traditional resistance training [241]. The nature of hypertrophy appears to differ with eccentric training versus concentric training and the addition of sarcomeres in series, as inferred from changes in muscle fascicle length, may contribute to increases in CSA [70, 194]. A greater number of sarcomeres in series may subsequently increase muscle shortening velocity and increase force production at longer muscle lengths [2]. Fast twitch fibres hypertrophy to a greater extent as a consequence of eccentric training [71,

72], and while further research is required, it is possible an upregulation of IIx mRNA signalling can occur [71, 259], leading to an attenuated IIx to IIa shift [74, 196, 255], or an increase in IIx composition with fast contractions [75]. An increased number of sarcomeres in series, selective fast twitch fibre hypertrophy, and possibly increased IIx composition, have been collectively referred to as a shift towards a faster phenotype [2], and may contribute to improvements in speed and power performance with eccentric training. Furthermore, increases in tendon stiffness [69] and CSA [237] will aid the storage and return of elastic strain energy during SSC movements. Particular consideration should be given to contraction velocity; fast eccentric training appears to induce the largest improvements in strength, power and SSC performance [63, 76], and further stimulate increases in muscle CSA [76] and IIx fibre composition [75]. While fast contractions *per se* are probably an important stimulus, further research is necessary in elucidating the influence of a markedly lower time under tension with such protocols [77]. An acute eccentric training intervention in untrained participants seems to follow the typical adaptive pattern with resistance training. The largest increases in early phase strength (i.e. 3-4 weeks) are underpinned by neural factors, while MTU morphological and architectural changes require a longer time to materialise [246]. As residual fatigue with eccentric exercise can suppress force production and affect neural control for a period of time following the cessation of training, an appropriate recovery window (i.e. up to 8 weeks) may be necessary to fully realize neuromuscular adaptations [236]. It is less clear how these findings translate to resistance trained subjects as the majority of investigations have recruited untrained participants; it has been suggested that the pattern of adaptation may be similar, but of a lower magnitude [2]. The heterogeneity of protocols used makes it difficult to elucidate best practice in training volume and frequency. Presently, it would seem that the management of EIMD and delayed-onset muscle soreness should be a primary consideration. Further research is necessary to determine the optimal progression of load and contraction velocity, especially in resistance trained subjects, for the MTU and performance outcomes.

A Novel Isoinertial Assessment of Lower Limb Eccentric Strength

4.0 Lead Summary

The novel aspects of eccentric contractions, and subsequently, superior improvement in neuromuscular qualities related to strength, speed and power performance with eccentric training have been highlighted in the previous chapters. In addition, eccentric muscle function (e.g. strength) is thought to play an important role in SSC function and a range of athletic performance tasks. Therefore, a practically accessible assessment of lower body eccentric strength during functional multi-articular movement (i.e. back squat) is of substantial utility to athletic testing and training. Previous investigations assessing isoinertial eccentric strength have relied upon subjective methods to discern eccentric failure which may introduce intra- and inter-rater error. There were three objectives of this study; 1) investigate the reliability of a practical method of determining isoinertial eccentric back squat strength using a novel objective criteria, 2) determine if mean and peak eccentric force in the back squat could be validly predicted using position-time data, and 3) determine the difference between the eccentric and concentric back squat 1RM in resistance trained participants. Ten resistance trained males (Mean ± SD: 26 ± 4 y, 83 ± 19 kg, 1.81 ± 0.10 m, relative concentric back squat 1RM: 1.75 ± 0.25 kg·BM^{-1}) completed one concentric strength testing and familiarization session, and three reliability testing sessions separated by seven days. During familiarization and reliability testing sessions participants completed a novel eccentric 1RM protocol. Using the novel criteria, the protocol objectively delineated a successful repetition from an unsuccessful repetition. Actual bar velocity in the bottom third of the squat (i.e. 120-90°) was largely higher at 105% 1RM versus 100% 1RM (Effect Size [ES] ±90% Confidence Limits [CL]: 1.32 ±0.87, $p < .05$), reflecting a loss of control, while no differences were observed between 94% 1RM and 100% 1RM. Actual bar velocity in the bottom third of the squat exhibited acceptable inter-day reliability at 94%, 100% and 105% of the eccentric 1RM (coefficient of variation [CV]: 5.3-11%; intra-class correlation coefficient [ICC]: 0.63-0.70). Accordingly, the eccentric 1RM and subsequently mean eccentric force exhibited very high absolute inter-day reliability (CV <1%; ICC: >0.99), while position-time data validly predicted mean force but not peak force during the eccentric 1RM. Finally, it was identified that resistance trained males were 28 ± 8% (ES 1.02 ±0.64) stronger during an eccentric 1RM than a concentric 1RM. Therefore, this novel method of assessing isoinertial eccentric back squat strength in a practical setting can be reliably used in athlete testing.

It also appears that eccentric phase duration alone (i.e. tempo) is insufficient in identifying eccentric failure. Furthermore, knowledge of the approximate back squat eccentric-to-concentric strength ratio in resistance trained males provides a guideline for the prescription of resistance training intensity within an eccentric training program utilizing this movement.

4.1 Introduction

Muscular strength is an important determinant of sporting performance, either directly, or via its influence on other physical qualities (e.g. muscular power and absolute RFD) [189, 191, 271, 272]. Strength is primarily measured via isoinertial, isokinetic or isometric assessments [273]. Eccentric muscle function is important for a range of athletic tasks [2], the determination of maximum eccentric muscle strength is therefore of interest. Eccentric contractions occur when the external load exceeds the momentary force produced by the agonist musculature [35]. Isokinetic dynamometry remains the gold standard method of assessing eccentric strength, however, the control afforded by isokinetic testing is also a limitation in its questionable representativeness of dynamic strength during functional multi-articular tasks [79] and requires equipment that is not readily accessible to those working in practical settings. It is more difficult to determine eccentric strength using isoinertial assessments. In contrast to concentric strength testing where the load is either successfully overcome or not, isoinertial eccentric strength testing has relied on a subjective evaluation of control throughout the range of motion of the task, or a minimum repetition duration guided by a metronome [43, 80]. While the use of a metronome is an improvement over visual observation alone, it is possible that intra- and inter-rater error impact the sensitivity and reliability of this assessment. An alternative isoinertial assessment has used a fixed bar within a smith machine whereby participants stood on a force platform and performed a back squat with a standardised mass that they could control but not arrest (i.e. 200% body mass) [274]. From the force platform, the researchers determined peak force and peak RFD. While reducing the subjectivity of the assessment, this protocol still relies on expensive equipment (i.e. a force platform) and given the ascending strength curve of the back squat [275-277], peak force is likely occurring near the top of the movement. Thus, the assessment provides little insight into eccentric strength of the hip and knee extensors through a large range of motion (i.e. a parallel squat). Furthermore, no reliability analysis was reported for this protocol.

The development of a practical isoinertial eccentric strength assessment that can objectively delineate a successful repetition from an unsuccessful repetition, and exhibits acceptable reliability is therefore of interest to athletic performance. The

purpose of this investigation was threefold; 1) investigate the reliability of a practical method of determining isoinertial eccentric back squat strength using a novel objective criteria, 2) determine if mean and peak eccentric force in the back squat could be validly predicted using position-time data, and 3) determine the difference between the eccentric and concentric back squat 1RMs in resistance trained participants.

4.2 Methods

4.2.1 Experimental overview

A cross-sectional, repeated measures design was used with participants completing one concentric back squat 1RM determination and familiarization session, and three reliability testing sessions separated by seven days (i.e. four sessions per participant over 4-weeks). Testing was performed at approximately the same time of day (i.e. ± 2 hours), and within the same strength and conditioning laboratory.

4.2.2 Participants

Ten resistance-trained males (Mean ± SD: 26 ± 4 y, 83 ± 19 kg, 1.81 ± 0.10 m, relative back squat 1RM: 1.75 ± 0.25 kg·BM^{-1}) were recruited. This sample size was selected to balance study power with practicality, and was based upon previous recommendations to include a minimum of 10 participants within such a design [278]. Participants had at least one year of experience with regular (≥ 2x per week) resistance training and were free of injury and illness which would affect exercise performance. Informed consent was completed and all testing protocols complied with AUT ethical guidelines. All testing protocols were approved by the University Ethics Committee.

4.2.3 Concentric back squat 1RM determination and familiarization

Participants were provided with an overview of all study procedures followed by the completion of informed consent. They completed a PAR-Q questionnaire to screen for contraindications that would predispose them to an elevated risk of a cardiac event or musculoskeletal injury. Descriptive information was collected including height and body mass. Participants then completed a concentric 1RM assessment of the back squat. The 1RM test was completed in a smith machine and participants were required to descend to a knee angle of 90° as determined by a goniometer. The protocol has been described previously [273], following four warm up sets the load was increased until the resistance could not be overcome, with the intention of attaining the 1RM within three attempts. Following the concentric 1RM assessment participants were familiarized with the eccentric back squat protocol and an approximate eccentric 1RM was determined.

4.2.4 Eccentric back squat 1RM determination

The eccentric back squat 1RM was determined as the maximum load that could be controlled at a consistent descent velocity to parallel (i.e. a knee angle of 90°). The back squat was performed in a custom-made smith machine (Goldmine, HPSNZ, Auckland, New Zealand) which provided pneumatic assistance during the concentric phase of the movement. Concentric load was therefore limited to ≤ 60kg for all repetitions. Range of motion was individualized using two triggers, one at the top of the movement and one at the bottom the movement (i.e. to initiate the onset of the concentric assistance). Participants were required to descend with the load at a constant velocity for 3-seconds (i.e. approximately 30°/s), feedback was provided by a linear position transducer (LPT) fitted to the bar sampling at 250 Hz (Goldmine, HPSNZ, Auckland, New Zealand) which measured bar velocity (m.s^{-1}) and eccentric phase duration (s). Live bar position-time data and a target graphic were displayed on a large digital screen in front of participants to aid in the attainment of the prescribed movement speed. During familiarization participants completed warm up sets at 50% (5 repetitions), 80% (3 repetitions) and 110% (1 repetition) of their concentric back squat 1RM, followed by

increases of 5% until there was a clear failure to control the descent at the allocated velocity [43, 80]. Individual variation in descent velocity was also determined as the mean standard deviation in bar velocity across each third of the descending range of motion (i.e. 180-150°, 150-120°, and 120-90°) of the final three successful attempts of the familiarization session. During the reliability testing sessions participants completed warm up sets at 50% (5 repetitions), 70%, 85%, and 95% (1 repetition each) of the approximate eccentric 1RM determined during familiarization. Attempts were made at increases of 5% thereafter, separated by 3-5 minutes of passive rest. Failure to control the load was expected to occur at a knee joint angle of approximately 100° [276]. Therefore, two criteria were used to ascertain isoinertial eccentric failure during the reliability trials; 1) the clear failure to control the descent at the allocated velocity; and 2) an increase in bar velocity during the bottom third of the range of motion (i.e. 120-90°) that was two standard deviations above the individual variation in bar velocity (i.e. termed the velocity failure threshold) determined during familiarization. This method provided an additional objective criteria for eccentric failure compared with previous investigations which exclusively utilized a metronome and subjective evaluation [43, 80]. Figure 4.1 provides an example from a single participant of one final successful repetition (i.e. the eccentric 1RM) and one failed repetition (i.e. eccentric failure), respectively.
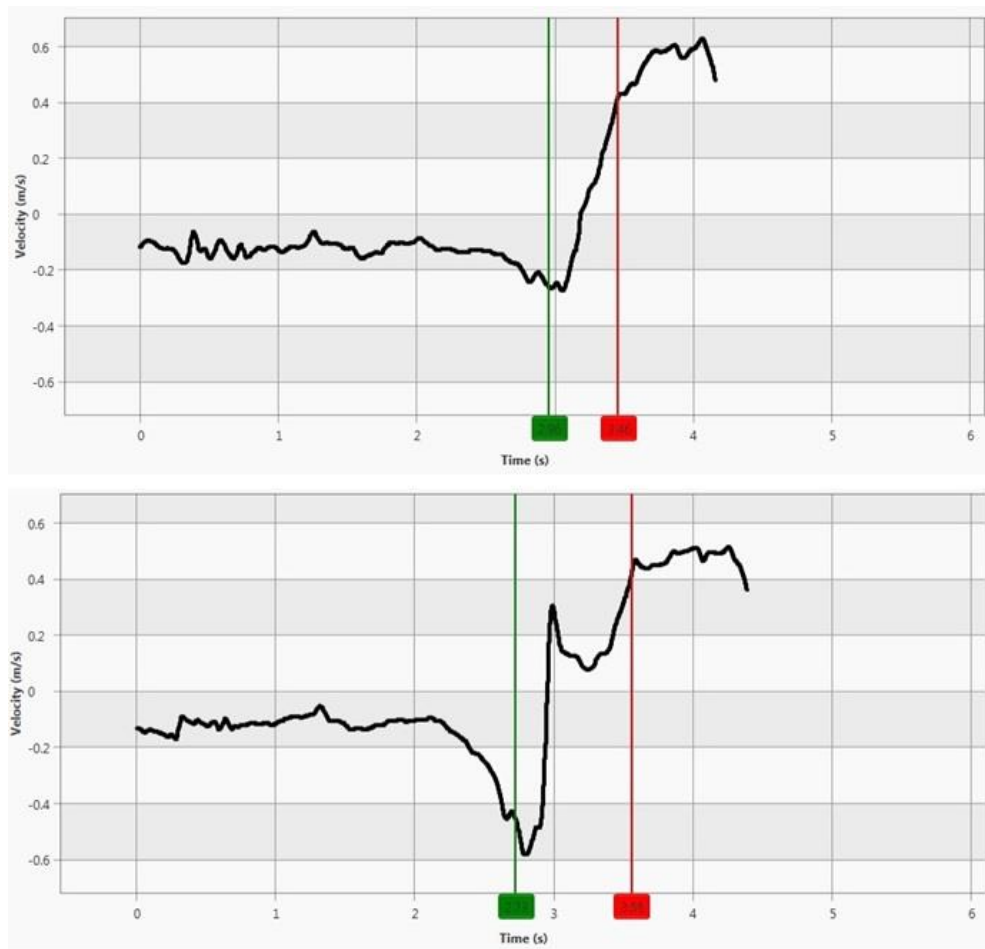
Figure 4.1. Top: Velocity-time data for a single participant at a load corresponding to their eccentric back squat 1RM (i.e. a successful repetition). Bottom: Velocity-time data for the same participant at a load exceeding their eccentric 1RM by 5% whereby actual velocity exceeds the 'velocity failure threshold' (i.e. eccentric failure). The vertical green line represents the time at which the bottom trigger was reached at the end of the eccentric phase (i.e. 90° knee angle) and the pneumatic assist was applied. The vertical red line represents the time at which the top trigger was reached at the end of the concentric phase (not used for analysis).

4.2.5 Measurement and analysis of eccentric force

To determine whether the LPT could accurately predict mean and peak eccentric force via differentiation of displacement data, all trials at 95, 100 and 105% of the eccentric 1RM were completed concurrently on a force platform (FT700 Ballistic Measurement System, Fitness Technology, Adelaide, Australia) sampling at 600 Hz. The LPT was calibrated to a known distance, and the force platform to a known mass prior to each testing session. Average and peak forces from the LPT were determined using differentiation of velocity and the known mass within the software program (Goldmine, HPSNZ, Auckland, New Zealand), while raw force platform data were exported and analyzed in Microsoft Excel. The end of each repetition within the force-time curve could be clearly identified by the onset of the pneumatic lift assist and therefore using the known repetition duration from the LPT the repetition was identified and analyzed.

4.3 Statistical Analysis

Means and standard deviations (SD) were used to represent the centrality and spread of data. A statistical spreadsheet was used to calculate standardised differences (i.e. Cohen's *d*), or ES (with 90 % confidence intervals [CI] and CL) using the pooled SD [279] alongside paired student *t*-tests (α: .05) to ascertain the differences between loads for selected variables. The smallest worthwhile change or difference was calculated as 0.2 multiplied by the between subject SD [279]. Threshold values for effect size statistics were set as: ≤ 0.2 trivial/unclear, > 0.2 small, > 0.6 moderate, > 1.2 large, > 2.0 very large, and > 4.0 extremely large [280]. The reliability of measures were determined via the average change in the mean across the three trials and therefore the typical error of measurement (TEM), the absolute (%) reliability (i.e. within-subject variation) via the CV, and relative via retest correlations (i.e. the consistency of the rank of a participant in relation to others) via the ICC were used [281, 282]. Variables were considered to have acceptable reliability if CV values were $\leq 10\%$ and/or ICC values were ≥ 0.70, and unacceptable reliability if neither were met [283]. The practical measure (i.e. LPT) was validated against the 'gold standard' criterion measure (i.e. force platform) via the Pearson correlation (*r*), the mean difference in raw units and the

bias as a percentage (%) difference. The practical measure was considered valid if both $r \geq 0.90$ and the mean bias was $\leq 5\%$.

4.4 Results

The eccentric back squat 1RM was higher than concentric 1RM (184 ± 35 vs. 144 ± 27 kg; ES ±90% CL: 1.02 ±0.64) with an eccentric to concentric 1RM ratio ($kg \cdot kg^{-1}$) of 1.28 ± 0.08 $kg \cdot kg^{-1}$ (Figure 4.2).
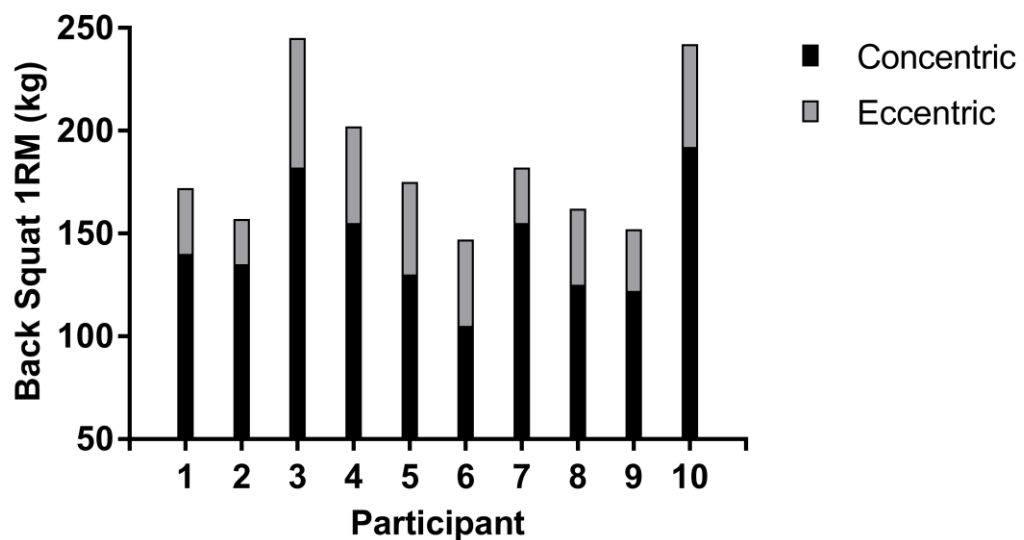
Figure 4.2. Individual concentric and eccentric back squat one repetition maximum (1RM) for all ($n = 10$) participants.

Because of the smallest possible loading increments (i.e. 2 kg), the mean submaximal load was completed at 94% of the final eccentric 1RM. There were no differences in the velocity failure threshold between any load (ES ±90% CL: 0.01 ±0.65, -0.40 ±0.69, $p >$ .05, for 94 vs. 100%, and 100 vs. 105%, respectively) indicating that the movement velocity of the top two thirds of the range of motion remained consistent across loads (Table 4.1). Actual movement velocity within the bottom third was moderately lower

than the velocity failure threshold at 94 and 100% of the eccentric 1RM (ES: -0.75 ±0.78, and -0.43 ±0.80, $p < .05$, respectively) and was largely higher than the velocity failure threshold at 105% of the eccentric 1RM (ES: 1.72 ±1.09, $p < .01$). Furthermore, there was a large increase in actual velocity at 105% vs. 100% (ES: 1.32 ±0.87, $p < .05$) indicating a loss of control. There were no clear differences in eccentric phase duration between 94 and 100% (ES: -0.07 ±0.81, $p > .05$), or 100 and 105% (ES: 0.23 ±0.70, $p > .05$), indicating that repetition duration alone was not sensitive enough to delineate successful and unsuccessful trials.

The reliability of key variables from the eccentric back squat protocol at loads of 94, 100 and 105% of the eccentric 1RM are reported in Table 4.2. There were no differences in the identified load that elicited a loss of control and eccentric failure across the three trials. Accordingly, mean force remained acceptably reliable at each load. The duration of the eccentric phase exhibited similar absolute and relative reliability across loads of 94, 100 and 105%. The velocity failure threshold remained consistently reliable at 94 and 100%, although relative reliability was affected at 105%. The actual velocity exhibited lower relative reliability, particularly at 94%, however, exhibiting higher reliability at 100 and 105%.

Table 4.1. Reliability of variables determined from a novel assessment of isoinertial lower limb eccentric strength in resistance trained individuals ($n = 10$) at 94%, 100% and 105% of the eccentric 1RM.

	Trial 1 Mean ±SD	Change in the Mean (90% CI)		TEM (90% CI)	CV (90% CI)	ICC (90% CI)
		Trial 2-1	Trial 3-2			
94% Eccentric 1RM						
Load (kg)	172.5 ± 35.8					
Mean Force (N)	1683 ± 350	-1 (-7; 5)	2 (-3.4; 7.3)	7 (5; 10)	0.3 (0.2; 0.4)	1.00 (1.00; 1.00)
Duration (s)	3.27 ± 0.46	-0.01 (-0.14; 0.13)	-0.1 (-0.4; 0.2)	0.28 (0.22; 0.41)	7.5 (5.6; 13.2)	0.68 (0.36; 0.88)
Velocity Failure Threshold (m·s⁻¹)	0.18 ± 0.03	0.00 (-0.01; 0.01)	0.00 (-0.01; 0.02)	0.01 (0.01; 0.02)	6.6 (4.7; 11.3)	0.84 (0.64; 0.94)
Actual Velocity (m·s⁻¹)	0.16 ± 0.04*	0.00 (-0.01; 0.02)	0.00 (-0.02; 0.01)	0.02 (0.02; 0.03)	11.0 (6.0; 17.0)	0.70 (0.39; 0.89)
100% Eccentric 1RM						
Load (kg)	183.6 ± 35.3					
Mean Force (N)	1790 ± 343	0 (-4; 4)	-1 (-5; 3)	5 (4; 7)	0.2 (0.1; 0.4)	1.00 (1.00; 1.00)
Duration (s)	3.24 ± 0.58	0.04 (-0.12; 0.21)	-0.26 (-0.48; -0.03)	0.24 (0.19; 0.35)	6.8 (4.3; 11.1)	0.80 (0.56; 0.93)
Velocity Failure Threshold (m·s⁻¹)	0.18 ± 0.03	0.00 (-0.01; 0.01)	0.01 (0.00; 0.02)	0.01 (0.01; 0.01)	10.0 (6.8; 16.8)	0.87 (0.69; 0.95)
Actual Velocity (m·s⁻¹)	0.17 ± 0.03*	-0.01 (-0.02; 0.00)	0.02 (0.01; 0.03)	0.02 (0.01; 0.02)	5.3 (3.2; 8.5)	0.69 (0.37; 0.88)
105% Eccentric 1RM						
Load (kg)	193.5 ± 35.7					
Mean Force (N)	1883 ± 347	-2 (-7; 3)	-3 (-6; 0)	5 (4; 7)	0.3 (0.2; 0.5)	1.00 (1.00; 1.00)
Duration (s)	3.38 ± 0.56	-0.24 (-0.60; 0.13)	-0.02 (-0.25; 0.22)	0.37 (0.29; 0.55)	9.5 (5.7; 15.2)	0.61 (0.26; 0.85)
Velocity Failure Threshold (m·s⁻¹)	0.17 ± 0.02	0.01 (0.00; 0.01)	0.00 (-0.01; 0.01)	0.01 (0.01; 0.01)	13.3 (10.7; 24)	0.90 (0.75; 0.96)
Actual Velocity (m·s⁻¹)	0.22 ± 0.05*†	0.02 0.01; 0.06)	-0.01 (-0.02; 0.01)	0.03 (0.02; 0.05)	5.7 (4.0; 9.8)	0.63 (0.28; 0.85)

Abbreviations: 1RM: one repetition maximum; CI: confidence interval; CV: coefficient of variation; ICC: intra-class correlation coefficient; kg: kilograms; m·s⁻¹: metres per second; N: newtons; s: seconds; SD: standard deviation. * Difference between Velocity Failure Threshold and Actual Velocity ($p < .05$); † Difference between 105% 1RM versus 100% 1RM and 94% 1RM ($p < .05$).

A comparison of the mean and peak forces predicted by the LPT and those measured directly by the force platform across 94, 100 and 105% of the eccentric 1RM are reported in Table 4.2. Both mean and peak force were almost perfectly correlated between measures ($r > 0.90$), however there was a marked difference between measures in peak force at all loads (113-205 N) and a large bias (8.6-10.7%). The mean force was accurately predicted by differentiation of LPT position data at all loads with a smaller mean difference (9-14 N) and subsequently negligible bias (0.6-0.9%).

Table 4.2. Comparison of mean and peak force determined from a force platform and a linear position transducer (LPT) during an isoinertial eccentric back squat at loads of 94, 100 and 105% of the eccentric one repetition maximum ($n = 28$).

	Force Platform ±SD	LPT ±SD	Pearson Correlation (90% CI)	Mean Difference (90% CI)	Bias (90% CI)	Validity Classification
Mean Force (N)						
94%	1658 ± 326	1673 ± 325	1.00 (1.00; 1.00)	14 (8; 19)	0.9 (0.5; 1.1)	Valid
100%	1768 ± 327	1781 ± 319	1.00 (1.00; 1.00)	12 (5; 20)	0.8 (0.3; 1.1)	Valid
105%	1862 ± 327	1871 ± 322	1.00 (1.00; 1.00)	9 (3; 16)	0.6 (0.1; 0.9)	Valid
Peak Force (N)						
94%	1773 ± 333	1929 ± 399	0.98 (0.95; 0.99)	113 (86; 141)	8.6 (6.9; 10.7)	Invalid
100%	1885 ± 338	2091 ± 428	0.94 (0.89; 0.97)	205 (155; 255)	10.7 (8.2; 13.5)	Invalid
105%	1992 ± 346	2182 ± 424	0.96 (0.93; 0.98)	190 (148; 232)	9.3 (7.4; 11.6)	Invalid

Abbreviations: CI: confidence interval; N; newtons; SD: standard deviation.

4.5 Discussion

This study sought to determine whether a novel objective criteria could reliably assess eccentric back squat strength under isoinertial conditions, and whether mean and peak eccentric force in the back squat could be validly predicted using position-time data. Furthermore, the difference between the eccentric and concentric back squat 1RMs in resistance trained participants was also investigated. It was found that the velocity failure threshold provided an objective means of determining eccentric strength in the back squat. There was a statistically significant large difference in the ability to control the descent between loads of 100 and 105% of the eccentric 1RM as reflected in the actual velocity in the bottom third of the range of motion exceeding the velocity failure threshold at 105%. No such difference was observed between 94 and 100%. The variables which were used to ascertain control (i.e. duration, velocity failure threshold and actual velocity) exhibited acceptable inter-day reliability across three testing sessions. There were no differences in the load at which a loss of control occurred, and subsequently mean force exhibited acceptable reliability. The mean eccentric force applied during the repetition was accurately predicted by the LPT position data and therefore exhibited a high level of concurrent validity. Peak eccentric force predicted by the LPT exhibited a large bias (i.e. systematic offset) and was not a valid measure within this protocol. Finally, it was found that resistance trained males were approximately 28% stronger during the eccentric back squat 1RM protocol compared to the commonly used concentric back squat 1RM.

4.5.1 Validity and reliability of the isoinertial eccentric back squat protocol

This is the first study to implement an objective criterion to delineate an eccentric 1RM from eccentric 'failure' under isoinertial testing conditions. The load at which failure occurred remained consistent across the three trials which indicates that it is a reliable assessment in the absence of any obvious change in participant status (e.g. fitness, fatigue or arousal). It was possible that given the novelty of the protocol that there may have been a training effect across the four sessions hence all attempts were made to minimize the volume load of each testing session, accordingly, no such effect was observed. The manner in which each repetition was performed (i.e. duration and

movement velocity) also exhibited acceptable reliability across submaximal, maximal and supramaximal loads. Relative reliability (i.e. ICC) statistics were affected on a number of variables, likely due to the relatively homogeneous dataset resulting from the standardised tempo [281, 284]. It has been argued that absolute reliability (i.e. the CV) is the primary reliability statistic of interest to practitioners [285], and accordingly most variables were below 10%, and all were below 14%. As expected, at supramaximal loads, the loss of control as reflected in an increase in movement velocity occurred in the bottom third of the range of motion of the back squat to parallel (i.e. 90°) which reflects the 'sticking point' of the movement. The sticking point is the point where failure typically occurs when a given exercise is taken to momentary muscular failure or where movement velocity decreases at near-maximal loads [286]. In a multi-joint movement such as a back squat the strength curve reflects the composite length-tension and force-velocity characteristics of the contributing musculature and mechanical advantage of the external load [286]. The present study assumed that the eccentric strength curve would be equivalent to the ascending concentric strength curve of the back squat, the weakest point would be within the bottom region of the movement with the least mechanical advantage [275]. Indeed, previous research has identified the sticking region of the back squat to be at a relative knee joint angle of approximately 100° [276, 277]. The present data support this proposition with all participants exhibiting a relatively stable movement velocity across the top two thirds of the range and 'failure' occurring in the bottom third (i.e. 120-90°). Furthermore, these data suggest that in contrast to a reduction in concentric velocity throughout the sticking region, eccentric failure is characterised by an increase in eccentric velocity throughout the sticking region.

4.5.2 Utility of the isoinertial eccentric back squat protocol

Insight into eccentric muscle mechanical function may have implications for both research and practical settings. The eccentric back squat 1RM provides insight into the eccentric force producing capabilities of the hip and knee extensors which play an important role in sporting performance. Furthermore, the implementation of accentuated eccentric training using isoinertial methods may be more accurately prescribed with knowledge of the eccentric 1RM. If it is not practically feasible to implement such a

protocol the present study indicates that the eccentric 1RM is approximately 28% higher than the concentric 1RM in the back squat performed within a smith machine. This finding is somewhat lower than previous research which found that isoinertial eccentric back squat strength was approximately 38% higher than concentric strength in female basketball players [80]. The difference may be related to the resistance training status of the participants recruited. The present study recruited resistance trained males with a relative concentric 1RM of 1.75 kg·BM^{-1}, whereas the female basketball players had a relative 1RM of 0.96 kg·BM^{-1}. It has also been demonstrated that females exhibit a larger difference between eccentric and concentric strength than males [43]. Furthermore, the only method of control used within the previous study was eccentric phase duration. The present study indicates that this is not a sensitive means of identifying eccentric failure, and therefore the previous investigation may have overestimated the eccentric 1RM. In another study comparing eccentric to concentric strength across a range of isoinertial exercises, although not the back squat, it was found that eccentric strength was 20-60% higher than concentric strength in males [43]. In this study, the only multi-joint lower body movement assessed was the leg press which exhibited a ratio of 44% in males. It is possible that the smaller difference between eccentric and concentric strength in the present study could be due to the movement assessed. The back squat requires a full body stabilization with the load transferred through the back and spine whereas the upper body and trunk are largely unloaded in the leg press. Knowledge of the actual or predicted eccentric 1RM can therefore be used to prescribe loads in subsequent eccentric training. Given the differences in the fatigue profile between contraction types [48], it is possible that the relative intensity of eccentric training will differ to concentric or traditional resistance training. Although a previous investigation has identified that the eccentric and concentric repetition-load relationships (i.e. relative to the given eccentric or concentric 1RM) are comparable in the bench press exercise [287]. Finally, it is unclear whether these findings are applicable to movements with differing length tension characteristics, but it is proposed that this protocol could be used to discriminate eccentric strength within other movements that have an ascending strength curve (e.g. bench press).

4.5.3 Validity of the LPT in determining force production

Previous investigations have found forces predicted via LPT technology to be highly correlated with values determined from a force platform [285, 288, 289]. The force platform measures vertical ground reaction forces directly whereas the LPT involves differentiation of displacement data using the known system mass to predict instantaneous velocity, acceleration, and force [285]. While previous investigations have found the LPT to be a valid and reliable means of determining force during free-bar concentric exercise, it was less clear whether force could be accurately predicted during an eccentric back squat within a smith machine. The smith machine is designed to move vertically on relatively frictionless rails, but nonetheless, may still contain some friction. Additionally, it is possible that there is some dampening between the ground reaction force generated and what is transferred to the bar (i.e. some force lost with horizontal application into the rails). A previous study found no difference in free bar versus smith machine back squat 1RM in males [290]. If friction or an inefficient application of force were factors in comparing the smith machine with a free bar it would be expected that there would be a difference in the 1RM between devices, although differences in stability demands may have been a confounding factor [290]. Nonetheless, the present study demonstrated an almost perfect correlation between mean force predicted from the LPT and measured directly via a force platform. This indicates that under the conditions imposed in the present study (i.e. duration and velocity control) mean force can be validly predicted. Interestingly this finding was consistent across all loading conditions. It was expected that a failure in control as reflected in an increase in bar velocity (i.e. acceleration) would result in an over prediction of force. This was not the case and therefore a loss of control in the bottom third did not appear to influence predicted mean force. Irrespective of this finding, the mean force of a failed attempt is unlikely to be of interest to researchers and practitioners. While both mean and peak force were highly correlated between measures there was a marked overestimation of peak force. A previous investigation has found that LPT technology overestimated peak force during jump squats at 90 and 100% 1RM [291]. However, others have found peak force to be accurately predicted during jump squats at 30, 50 and 70% 1RM [289], 40kg [285], unloaded jump squats, countermovement jumps and DJs [288]. Peak force is arguably of little interest to researchers and practitioners within the context of the present protocol. The eccentric

1RM to 90° was chosen to provide insight into eccentric strength of the hip and knee extensors throughout a large range of motion. Under isoinertial conditions peak force is constrained by load applied to the bar which in turn is constrained by the sticking point of the movement. Therefore, the load corresponding to the eccentric 1RM and the corresponding mean force are likely sufficient in providing insight into an individual's eccentric strength levels.

4.5.4 Limitations

The limitations of this protocol should also be acknowledged. This protocol is likely only applicable to movements with similar length-tension and force-velocity characteristics, given the objective criteria and relatively slow contraction speed (i.e. ~30°/s) used to ascertain eccentric failure. At higher contraction speeds, it may be more difficult to identify the velocity failure threshold and therefore an objective determination of failure. Furthermore, while it is felt the inclusion of an objective criteria is an improvement upon subjective observation alone, the measurements for the objective determination of failure (i.e. velocity failure threshold) requires an initial familiarisation session, and therefore, a minimum of two testing sessions are necessary.

4.6 Conclusion

This protocol using a velocity failure threshold provided an objective means of determining an eccentric 1RM as distinct from eccentric failure. Eccentric phase duration alone was unable to discriminate a successful repetition from a failed repetition. The eccentric 1RM and the load at which failure occurred remained identical across three testing sessions, while the variables used to ascertain control throughout the range of motion exhibited acceptable inter-day reliability. In addition, the differentiation of LPT position data accurately predicted mean force versus the direct measurement of ground reaction force under submaximal, maximal and supramaximal eccentric conditions. The eccentric 1RM was found to be ~28% higher than the concentric 1RM, this information could be of use to practitioners looking to implement an accentuated eccentric training program using the back squat exercise. The use of an LPT (alongside

a custom designed software program) and a smith machine are sufficient to objectively and reliably determine eccentric lower limb strength under isoinertial conditions in a practical setting.

The Reliability of a Drop Jump Phase Analysis

5.0 Lead Summary

The previous chapter investigated a novel protocol for assessing lower limb eccentric strength under isoinertial conditions that could be implemented within a practical environment. It is also challenging to assess eccentric muscle function under SSC conditions *in vivo* within practical settings. High force fast SSC function is typically inferred from the RSI (flight time [or jump height] divided by contact time) obtained from DJ or hopping tasks. While the RSI is a useful performance measure, it does not account for the relative role of eccentric or concentric phase characteristics in fast SSC performance. An analysis of the braking and propulsive phase kinetic variables underpinning DJ performance is proposed to provide insight into eccentric and concentric phase MTU contributions to high force fast SSC function. The purpose of this study was to determine the reliability of DJ performance, and braking and propulsive phase kinetic variables across a range of drop heights typically used in research and practice. Thirteen trained sprint athletes completed one familiarization session and three reliability testing sessions. DJs were performed bilaterally from 0.25m, 0.50m and 0.75m onto a force platform. Absolute and relative reliability were determined via the CV and ICC, respectively. All performance measures (including contact time, flight time, RSI and leg stiffness) exhibited acceptable reliability during all conditions (CV: 2.5-11.0%; ICC: 0.83-0.97). All braking phase variables (time, force, power, and impulse) demonstrated acceptable absolute reliability (CV: 4.7-8.6%), however relative reliability of braking impulse was low (ICC: 0.38-0.75). All propulsive phase variables exhibited acceptable reliability (CV: 2.4-8.2%; ICC: 0.75-0.97). These results align with previous reports and indicate that DJ performance variables exhibit acceptable inter-day reliability. Furthermore, all braking and propulsive phase variables underpinning DJ performance demonstrated acceptable reliability. Relative reliability of braking impulse was affected by the standardised drop heights and homogeneity of data. A DJ phase analysis is therefore a reliable method of assessing reactive strength (i.e. fast SSC function) and underlying braking and propulsive phase kinetic variables. Based on previous *in vivo* research it is proposed that this analysis method can provide insight into eccentric and concentric MTU contributions to fast SSC function.

5.1 Introduction

Effective SSC function plays an important role in powerful and efficient human movement [1, 6, 7]. SSC function is maximized by a well-timed agonist pre-activation, a short and forceful eccentric phase, and a brief coupling time between amortization and concentric phases [14]. Under such conditions concentric power output is enhanced due to the storage and return of elastic energy, stretch reflex potentiation, and time available for force production [14]. The relative contribution of these factors is likely related to the time available to complete the task [292]. Indeed, fast and slow SSC components have been distinguished based upon cycle duration [81]. Fast SSC movements are typically <0.25s, are characterized by high joint forces and small joint ranges of motion (e.g. ground contact phase of sprinting, long- and high-jump take-offs) [2]. Whereas, slow SSC movements are >0.25s and involve lower joint forces with larger ranges of motion (e.g. countermovement jumping) [2]. In research and practical settings fast SSC function is considered synonymous with reactive strength, and given its relevance to a range of athletic movements [16, 17], the ability to assess this quality is of great interest to both researchers and practitioners. A common assessment of lower limb (i.e. primarily knee and ankle) reactive strength is the DJ, which involves dropping from a given height and, immediately upon landing, reversing the movement and performing a maximal jump [293]. While contact time, flight time and jump height can be determined from each jump, arguably the best overall representation of fast SSC capabilities is the RSI.

The RSI is a product of jump height (or more directly, flight time) divided by ground contact time [16]. While the determination of RSI from a single drop height (i.e. braking, or stretch load) is commonly used in practice, the implementation of a range of drop heights can provide insight into an 'optimal' stretch load for the storage and return of elastic strain energy. Beyond this optimal braking load, the braking forces cannot be as rapidly absorbed resulting in extended ground contact times, while an inhibition of the short latency reflex potentiation may also impair flight time [81, 292]. Subsequently, a lower RSI score is observed. The RSI is a useful indicator of fast SSC function under standardised braking loads (i.e. drop heights); however, it remains unclear how reactively strong athletes attain a given score (i.e. a brief contact time, a long flight time, or an optimal compromise between the two). Furthermore, the relative

contribution of eccentric and concentric muscle function to reactive strength is also not well understood. It is thought that eccentric muscle function in particular is integral to fast SSC performance [14], and therefore the ability to reliably infer eccentric muscle function from a practical assessment is of substantial utility to researchers and practitioners seeking to test and develop fast SSC performance in trained athletes. Based on previous research measuring MTU activity *in vivo* during comparable fast SSC tasks [9, 11, 12], it is proposed that braking and propulsive phase kinetic variables assessed by a DJ phase analysis will provide insight into eccentric and concentric muscle function under fast SSC conditions.

Previous research has demonstrated that performance measures (e.g. contact time, flight time and RSI) exhibit acceptable intra- and inter-day reliability in the athletic population across a range of drop heights [294-296]. However, to date there has been no investigation into the reliability of braking and propulsive phase kinetic variables in trained sprint athletes. Therefore, the purpose of this study was to determine the test-retest reliability of performance measures, and braking and propulsive phase kinetic variables (i.e. a DJ phase analysis) during DJs performed from three increasing drop heights typically used in practice.

5.2 Methods

5.2.1 Experimental overview

A cross-sectional, repeated measures design was used and participants completed one descriptive information and familiarization session followed by three reliability trials. All sessions were separated by a minimum of three days and a maximum of seven days. Testing was performed at approximately the same time of day (i.e. ± 2 hours), and within the same strength and conditioning laboratory. During each session participants completed bilateral DJs from three increasing drop heights onto a force platform. Performance and kinetic variables were determined within braking and propulsive phases respectively. Absolute and relative inter-session test-retest reliability were determined from the three trials.

5.2.2 Participants

Thirteen competitive sprint athletes (8 males and 5 females) participated in the study (Mean ± SD: 23.3 ± 5.8 y, 73.2 ± 9.1 kg, 176.5 ± 8.9 cm). This sample size was selected to balance study power with practicality and was based upon previous recommendations to include a minimum of 10 participants within such a design [278]. All athletes had represented New Zealand in international competition in track and field, or beach flag sprinting. Participants were in their off-season at the time of testing with the focus of training being general physical preparation and basic strength. All participants were free of injury or illness which could affect jumping performance at the time of testing. Informed consent was completed and all testing protocols complied with AUT ethical guidelines. All testing protocols were approved by the University Ethics Committee.

5.2.3 Familiarization

During the descriptive information and familiarization session participants were provided with an overview of all study procedures, and completed a PAR-Q questionnaire to screen for contraindications that would predispose them to an elevated risk of a cardiac event or musculoskeletal injury. Descriptive information was collected including height and body mass. Participants were then familiarized with the DJ protocol.

5.2.4 Drop jump protocol

A general warm up was completed consisting of 3-minutes light exercise on a stationary cycle ergometer (95C Lifecycle, Life Fitness, Hamilton, New Zealand), followed by 5-minutes of dynamic mobility and callisthenic exercises addressing the lower limb musculature to be assessed (i.e. hip, knee & ankle extensors). The DJ assessment was completed bilaterally from three drop heights of 0.25m, 0.50m and 0.75m. Participants completed one practice jump for each condition followed by three maximal attempts (i.e. 12 jumps in total) with 30-seconds of recovery between each trial and 60-seconds between each height. The three maximal attempts were averaged and used for data

analysis. Participants were instructed to perform the DJ with hands akimbo, and to step forward from the box. They were explicitly asked to simultaneously attempt to minimize their ground contact time while maximizing their jump height, but to prioritize a brief ground contact time [293]. Trials in which technique was notably compromised were excluded and repeated. DJs were performed from a plyometric box onto an AMTI force platform sampling at 1000 Hz (AMTI, Watertown, MA, USA). A custom-designed LabView (National Instruments; version 8.2, Austin, TX, USA) program was used to collect and analyse the data.

5.2.5 Data analysis

A fourth-order Butterworth low-pass filter with a cut-off frequency of 200 Hz was used to smooth all force-time data. A vertical force threshold of 30 N was used to establish zero force and remove noise of the unweighted platform. The deviation from zero force was used to demarcate the beginning and end of the ground contact phase, and the end of the flight phase. Flight time was used to estimate vertical take-off velocity of the centre of mass. From which the change in velocity and body mass was then used to estimate the propulsive impulse. Braking impulse was determined via the subtraction of the propulsive impulse from the net or total impulse measured during the ground contact phase as derived from the force-time curve. The time point marking the transition from braking to propulsive impulse within the contact phase was calculated by the summation of fractional (sample by sample) impulse from the point of initial contact to when the sum was equal to the prior calculated negative or breaking impulse. This time point was used to define the braking and propulsive phases. From braking impulse and body mass the estimated landing velocity and drop height of the centre of mass were calculated. Acceleration of the centre of mass for the DJ was determined via the division of the measured force by known body mass and velocity was then determined via the integration of the acceleration data. Power was then calculated from the force and velocity data. Force- and power-time data parameters of interest were phase duration (s), peak and mean force ($N\cdot kg^{-1}$), peak and mean power ($W\cdot kg^{-1}$), and impulse ($N\cdot s^{-1}\cdot kg^{-1}$) within the braking and propulsive phases. Contact time (s), flight time (s), and RSI (flight time divided by contact time) were also determined. Leg spring

stiffness ($kN \cdot m \cdot kg^{-1}$) was calculated for each DJ using a method described previously [297]:

$$K_{Leg} = \frac{M \cdot \pi (T_f + T_c)}{T_c^2 \left(\frac{T_f + T_c}{\pi} - \frac{T_c}{4} \right)} \quad \text{(in } N \cdot m^{-1})$$

Where M is total body mass, T_c is contact time, and T_f is flight time. This value was subsequently converted from $N \cdot m^{-1}$ to $kN \cdot m^{-1}$ and divided by body mass.

5.3 Statistical Analysis

Means and SDs were used to represent the centrality and spread of data. The reliability of measures was determined via the average change in the mean across the three trials. Therefore, the TEM, the absolute (%) reliability (i.e. within-subject variation) via the CV, and relative reliability via retest correlations (i.e. the consistency of the rank of a participant in relation to others) and the ICC were used [281, 282]. Variables were considered to have acceptable reliability if CV values were ≤ 10% and/or ICC values were ≥ 0.70, and unacceptable reliability if neither were met [283].

5.4 Results

The reliability of all DJ performance and kinetic variables for jumps performed from three drop heights can be seen in Tables 5.1-5.3. The performance measures including contact time (CV: 3.9-5.8%; ICC: 0.83-0.89), flight time (CV: 2.5-4.5%; ICC: 0.94-0.97), RSI (CV: 4.8-5.8%; ICC: 0.88-0.94) and leg stiffness (CV: 7.2-11%; ICC: 0.89-0.95) exhibited acceptable reliability across 0.25m, 0.50m and 0.75m drop heights. The reliability of braking and propulsive phase duration was acceptable (CV: 3.5-8.6%; ICC: 0.82-0.93) across all drop heights. Peak and mean braking and propulsive forces displayed acceptable reliability from all drop heights (CV: 3.2-7.7%; ICC: 0.84-0.95). Peak and mean braking and propulsive power exhibited acceptable reliability across all heights (CV: 3.7-8.2%; ICC: 0.75-0.95). The reliability of braking impulse was acceptable for the three bilateral drop heights (CV: 2.2-3.0%; ICC: 0.38-0.70), similarly

propulsive impulse was acceptable during all conditions (CV: 2.4-3.0%; ICC: 0.95-0.97).

Table 5.1. Inter-day reliability of performance and kinetic variables determined from a phase analysis of a bilateral drop jump from 0.25m (*n* = 13). Raw data presented as means and standard deviations (±SD), reliability data presented as means and 90% confidence intervals (90% CI).

Variable	Trial 1 Mean (±SD)	Change in the Mean (90% CI)		TEM (90% CI)	CV (90% CI)	ICC (90% CI)
		Trial 2-1	Trial 3-2			
Contact Time (s)	0.167 ± 0.034	0.004 (0.001; 0.008)	-0.008 (-0.023; 0.007)	0.014 (0.01; 0.02)	3.9 (1.5; 5.5)	0.83 (0.63; 0.93)
Flight Time (s)	0.498 ± 0.073	-0.001 (-0.013; 0.012)	-0.006 (-0.013; 0.002)	0.015 (0.012; 0.021)	2.5 (1.6; 4.1)	0.97 (0.93; 0.99)
RSI (s·s^{-1})	3.03 ± 0.43	-0.04 (-0.12; 0.04)	0.06 (-0.09; 0.20)	0.17 (0.14; 0.24)	4.8 (2.6; 7.4)	0.88 (0.74; 0.95)
Leg Stiffness (kN·m·kg^{-1})	0.48 ± 0.13	-0.01 (-0.02; 0.00)	0.02 (-0.01; 0.05)	0.03 (0.02; 0.04)	7.7 (2.9; 12.5)	0.95 (0.90; 0.98)
Propulsive Phase Variables						
Braking Time (s)	0.065 ± 0.016	0.001 (-0.002; 0.004)	-0.005 (-0.010; 0.001)	0.006 (0.005; 0.009)	5.8 (3.3; 9.1)	0.85 (0.68; 0.94)
Braking Peak Force (N·kg^{-1})	72 ± 15	-1.3 (-5.2; 2.6)	2.7 (0.0; 5.9)	5.1 (4.1; 7.2)	7.7 (5.6; 9.8)	0.87 (0.72; 0.95)
Braking Mean Force (N·kg^{-1})	42 ± 6	0.0 (-2.0; 1.1)	1.08 (0.00; 2.4)	2.1 (1.7; 2.9)	4.7 (3.0; 6.4)	0.86 (0.70; 0.94)
Braking Peak Power (W·kg^{-1})	-116 ± 30	1.3 (-6.7; 9.3)	-2.2 (-10.0; 5.5)	11.3 (9.1; 15.9)	8.2 (5.8; 10.5)	0.84 (0.67; 0.93)
Braking Mean Power (W·kg^{-1})	-55 ± 7	0.0 (-2.1; 1.1)	-0.5 (-3.2; 2.1)	3.1 (2.5; 4.4)	5.1 (3.4; 6.8)	0.80 (0.60; 0.92)
Braking Impulse (N·s·kg^{-1})	2.05 ± 0.12	-0.004 (-0.073; 0.064)	-0.025 (-0.052; 0.002)	0.075 (0.060; 0.105)	3.0 (1.5; 4.5)	0.66 (0.37; 0.85)
Propulsive Phase Variables						
Propulsive Time (s)	0.102 ± 0.020	0.003 (0.001; 0.005)	-0.004 (-0.011; 0.003)	0.008 (0.006; 0.011)	4.5 (2.3; 6.8)	0.86 (0.71; 0.94)
Propulsive Peak Force (N·kg^{-1})	58 ± 10	-0.3 (-2.0; 1.4)	2.0 (-0.8; 4.8)	3.3 (2.7; 4.7)	5.5 (3.3; 7.7)	0.91 (0.81; 0.97)
Propulsive Mean Force (N·kg^{-1})	34 ± 3	-0.4 (-1.1; 0.3)	0.2 (-1.1; 1.5)	1.5 (1.2; 2.2)	3.8 (2.3; 5.3)	0.84 (0.66; 0.93)
Propulsive Peak Power (W·kg^{-1})	73 ± 13	-0.6 (-5.5; 4.4)	2.3 (-1.6; 6.1)	6.4 (5.1; 9.0)	6.9 (4.5; 9.4)	0.79 (0.59; 0.91)
Propulsive Mean Power (W·kg^{-1})	43 ± 8	-0.9 (-4.2; 2.4)	1.0 (-1.3; 3.4)	4.1 (3.3; 5.8)	7.8 (5.0; 10.6)	0.80 (0.60; 0.92)
Propulsive Impulse (N·s·kg^{-1})	2.43 ± 0.36	0.005 (-0.054; 0.065)	-0.028 (-0.063; 0.008)	0.07 (0.06; 0.10)	2.4 (1.6; 3.3)	0.97 (0.93; 0.99)

Abbreviations: CI: confidence interval; cm; centimetres; CV: coefficient of variation; ICC: intraclass correlation coefficient; kN·m·kg^{-1}: kilonewtons per metre per kilogram; N·kg^{-1}: Newtons per kilogram; N·s·kg^{-1}: Newtons per second per kilogram; RSI: reactive strength index; s: seconds; SD: standard deviation; TEM: typical error of measurement; W·kg^{-1}: watts per kilogram.

Table 5.2. Inter-day reliability of performance and kinetic variables determined from a phase analysis of a bilateral drop jump from 0.50m ($n = 13$). Raw data presented as means and standard deviations (±SD), reliability data presented as means and 90% confidence intervals (90% CI).

Variable	Trial 1 Mean (±SD)	Change in the Mean (90% CI)		TEM (90% CI)	CV (90% CI)	ICC (90% CI)
		Trial 2-1	Trial 3-2			
Contact Time (s)	0.179 ± 0.039	0.000 (-0.008; 0.008)	-0.004 (-0.012; 0.003)	0.011 (0.009; 0.016)	4.8 (2.6; 7.4)	0.89 (0.76; 0.96)
Flight Time (s)	0.522 ± 0.068	-0.008 (-0.020; 0.003)	-0.008 (-0.018; 0.002)	0.015 (0.012; 0.022)	2.9 (2.3; 5.2)	0.96 (0.90; 0.98)
RSI (s·s⁻¹)	3.01 ± 0.55	-0.08 (-0.19; 0.03)	0.03 (-0.12; 0.17)	0.18 (0.15; 0.26)	5.8 (4.0; 9.8)	0.89 (0.77; 0.96)
Leg Stiffness (kN·m·kg⁻¹)	0.42 ± 0.12	-0.01 (-0.03; 0.01)	0.01 (-0.01; 0.04)	0.03 (0.02; 0.04)	8.6 (4.8; 12.2)	0.94 (0.87; 0.98)
Braking Phase Variables						
Braking Time (s)	0.072 ± 0.019	0.001 (-0.005; 0.006)	-0.002 (-0.005; 0.002)	0.006 (0.005; 0.009)	6.6 (4.0; 10.5)	0.83 (0.66; 0.93)
Braking Peak Force (N·kg⁻¹)	91 ± 23	-2.04 (-7.2; 3.1)	0.4 (-4.3; 5.1)	7.1 (5.7; 10.0)	7.4 (4.7; 10.0)	0.89 (0.77; 0.96)
Braking Mean Force (N·kg⁻¹)	51 ± 8	-1.1 (-3.1; 0.9)	0.7 (-0.9; 2.2)	2.6 (2.1; 3.6)	5.3 (3.7; 6.9)	0.89 (0.76; 0.95)
Braking Peak Power (W·kg⁻¹)	-194 ± 54	6.0 (-6.0; 18.1)	2.1 (-6.6; 10.8)	15.1 (12.1; 21.2)	6.8 (3.9; 9.7)	0.90 (0.79; 0.96)
Braking Mean Power (W·kg⁻¹)	-84 ± 15	2.4 (-0.7; 5.4)	-0.4 (3.4; 2.7)	4.4 (3.5; 6.2)	5.9 (4.3; 7.5)	0.91 (0.81; 0.97)
Braking Impulse (N·s·kg⁻¹)	2.80 ± 0.11	-0.01 (-0.09; 0.07)	0.00 (-0.05; 0.05)	0.10 (0.08; 0.14)	2.6 (1.5; 3.7)	0.38 (0.04; 0.69)
Propulsive Phase Variables						
Propulsive Time (s)	0.107 ± 0.021	0.000 (-0.004; 0.003)	-0.003 (-0.008; 0.002)	0.006 (0.005; 0.009)	4.5 (2.5; 7.0)	0.89 (0.76; 0.96)
Propulsive Peak Force (N·kg⁻¹)	59 ± 12	-0.9 (-3.4; 1.6)	0.8 (-1.3; 2.9)	3.3 (2.7; 4.7)	6.1 (4.0; 8.1)	0.93 (0.85; 0.97)
Propulsive Mean Force (N·kg⁻¹)	35 ± 4	-0.4 (-1.2; 0.3)	0.2 (-1.0; 1.3)	1.4 (1.1; 2.0)	4.0 (2.8; 5.3)	0.89 (0.76; 0.95)
Propulsive Peak Power (W·kg⁻¹)	78 ± 14	-2.7 (7.1; 1.6)	2.2 (1.8; 6.1)	6.0 (4.8; 8.4)	6.3 (4.1; 8.5)	0.82 (0.63; 0.93)
Propulsive Mean Power (W·kg⁻¹)	45 ± 8	-1.2 (4.5; 2.0)	1.2 (-1.7; 4.0)	4.4 (3.5; 6.2)	7.3 (4.4; 10.2)	0.75 (0.51; 0.89)
Propulsive Impulse (N·s·kg⁻¹)	2.56 ± 0.34	-0.04 (-0.10; 0.02)	-0.04 (-0.09; 0.01)	0.08 (0.06; 0.11)	3.0 (2.3; 3.6)	0.96 (0.90; 0.98)

Abbreviations: CI: confidence interval; cm; centimetres; CV: coefficient of variation; ICC: intraclass correlation coefficient; kN·m·kg⁻¹: kilonewtons per metre per kilogram; N·kg⁻¹: Newtons per kilogram; N·s·kg⁻¹: Newtons per second per kilogram; RSI: reactive strength index; s: seconds; SD: standard deviation; TEM: typical error of measurement; W·kg⁻¹: watts per kilogram.

Table 5.3. Inter-day reliability of performance and kinetic variables determined from a phase analysis of a bilateral drop jump from 0.75m (n = 13). Raw data presented as means and standard deviations (±SD), reliability data presented as means and 90% confidence intervals (90% CI).

Variable	Trial 1 Mean (±SD)	Change in the Mean (90% CI)		TEM (90% CI)	CV (90% CI)	ICC (90% CI)
		Trial 2-1	Trial 3-2			
Contact Time (s)	0.191 ± 0.041	0.001 (-0.009; 0.011)	-0.008 (-0.016; 0.001)	0.013 (0.011; 0.019)	5.8 (3.8; 9.6)	0.89 (0.76; 0.95)
Flight Time (s)	0.522 ± 0.064	-0.015 (-0.026; -0.004)	-0.001 (-0.009; 0.008)	0.014 (0.011; 0.019)	2.7 (1.5; 4.2)	0.96 (0.92; 0.99)
RSI ($s \cdot s^{-1}$)	2.83 ± 0.56	-0.10 (-0.22; 0.01)	0.09 (0.01; 0.17)	0.14 (0.12; 0.20)	5.3 (3.3; 8.7)	0.94 (0.87; 0.98)
Leg Stiffness ($kN \cdot m \cdot kg^{-1}$)	0.38 ± 0.12	0.00 (-0.03; 0.03)	0.02 (-0.01; 0.04)	0.04 (0.03; 0.06)	11.0 (7.2; 14.7)	0.89 (0.77; 0.96)
Braking Phase Variables						
Braking Time (s)	0.076 ± 0.021	0.001 (-0.004; 0.007)	-0.005 (-0.010; 0.000)	0.007 (0.006; 0.011)	8.6 (6.2; 14.8)	0.86 (0.71; 0.94)
Braking Peak Force ($N \cdot kg^{-1}$)	112 ± 22	-2.3 (-7.9; 3.2)	0.0 (-3.6; 3.6)	6.7 (5.4; 9.4)	5.4 (3.6; 7.2)	0.93 (0.84; 0.97)
Braking Mean Force ($N \cdot kg^{-1}$)	57 ± 11	-1.2 (-4.3; 1.8)	1.8 (-0.9; 4.5)	4.1 (3.3; 5.8)	6.6 (4.7; 8.6)	0.88 (0.74; 0.95)
Braking Peak Power ($W \cdot kg^{-1}$)	-281 ± 51	10.9 (-4.5; 26.3)	5.3 (-10.6; 21.2)	22.4 (18.0; 31.6)	7.6 (5.5; 9.7)	0.82 (0.64; 0.93)
Braking Mean Power ($W \cdot kg^{-1}$)	-108 ± 25	4.4 (-1.5; 10.3)	-1.7 (5.9; 2.4)	7.3 (5.9; 10.3)	6.7 (4.4; 9.0)	0.92 (0.83; 0.97)
Braking Impulse ($N \cdot s \cdot kg^{-1}$)	3.6 ± 0.13	0.0 (-0.1; 0.1)	0.0 (-0.1; 0.1)	0.09 (0.07; 0.12)	2.2 (1.6; 2.8)	0.70 (0.44; 0.87)
Propulsive Phase Variables						
Propulsive Time (s)	0.115 ± 0.019	0.000 (-0.005; 0.005)	-0.003 (-0.007; 0.001)	0.007 (0.005; 0.009)	4.6 (2.8; 7.4)	0.89 (0.76; 0.96)
Propulsive Peak Force ($N \cdot kg^{-1}$)	54 ± 10	1.1 (-2.0; 4.1)	0.1 (-1.7; 1.9)	3.5 (2.9; 5.0)	5.7 (3.9; 7.4)	0.92 (0.82; 0.97)
Propulsive Mean Force ($N \cdot kg^{-1}$)	33 ± 4	-0.5 (-1.3; 0.2)	0.5 (-0.2; 1.2)	1.0 (0.8; 1.5)	3.2 (2.1; 4.4)	0.95 (0.88; 0.98)
Propulsive Peak Power ($W \cdot kg^{-1}$)	72 ± 12	-0.8 (-3.0; 1.5)	2.0 (0.0; 4.1)	3.1 (2.5; 4.4)	3.7 (2.3; 5.1)	0.95 (0.89; 0.98)
Propulsive Mean Power ($W \cdot kg^{-1}$)	41 ± 8	0.2 (-1.6; 2.0)	1.1 (-0.6; 2.7)	2.5 (2.0; 3.5)	5.2 (3.7; 6.6)	0.91 (0.81; 0.97)
Propulsive Impulse ($N \cdot s \cdot kg^{-1}$)	2.56 ± 0.31	-0.07 (-0.13; -0.01)	-0.01 (-0.05; 0.04)	0.08 (0.06; 0.11)	2.9 (1.7; 4.1)	0.95 (0.89; 0.98)

Abbreviations: CI: confidence interval; cm; centimetres; CV: coefficient of variation; ICC: intraclass correlation coefficient; $kN \cdot m \cdot kg^{-1}$: kilonewtons per metre per kilogram; $N \cdot kg^{-1}$: Newtons per kilogram; $N \cdot s \cdot kg^{-1}$: Newtons per second per kilogram; RSI: reactive strength index; s: seconds; SD: standard deviation; TEM: typical error of measurement; $W \cdot kg^{-1}$: watts per kilogram.

5.5 Discussion

The purpose of this study was to quantify the inter-day reliability of braking and propulsive phase kinetic variables underpinning bilateral DJ performance across three drop heights in trained athletes. Previous research has reported acceptable intra- and inter-day reliability of contact time, jump height and RSI determined from a DJ [294-296]. The findings from this study agree with previous research. Contact time, flight time, RSI and leg stiffness all demonstrated acceptable reliability. In addition, this is the first study to address the reliability of the braking and propulsive phase kinetic determinants of DJ performance in trained sprint athletes. These data demonstrate that all braking and propulsive phase kinetic variables were acceptably reliable during bilateral DJs from 0.25m, 0.50m and 0.75m. Irrespective of the drop height and therefore braking load, performance and kinetic variables exhibited acceptable reliability. Reactive strength tests are typically used to assess fast SSC function in research and practical settings. It is proposed that alongside commonly reported reactive strength performance measures such as contact time, flight time and RSI, the determination of braking and propulsive phase variables will provide additional insight into the role of eccentric and concentric muscle function in fast SSC performance in a practical setting.

5.5.1 Reliability of the DJ phase analysis

All braking and propulsive phase kinetic variables exhibited acceptable absolute reliability, and no obvious differences in reliability were found between braking and propulsive phases, or between drop heights. It should be noted that a low relative reliability for braking impulse was observed from all drop heights (ICC: 0.38-0.70). This was expected as braking impulse is determined exclusively by drop height and stepping technique. Therefore, independent of modest differences in technique which we endeavoured to control, braking impulse was standardised across participants resulting in a homogeneous dataset for this variable. This in turn impaired relative reliability via an attenuation of consistent rank-ordering between participants across trials [281, 284]. Within the braking phase of a DJ sufficient force must be produced to rapidly arrest the downward acceleration of the body mass before the propulsive phase

can be initiated [293]. The increasing drop heights with bilateral DJs increase the magnitude of acceleration and therefore necessary eccentric force and power production if a rapid contact time is to be achieved [293, 298]. With the exception of the absolute reliability of leg stiffness at 0.75m (CV: 11.0%), an increase in drop height and therefore braking load did not appear to notably affect the reliability values observed during DJs. It should be acknowledged that absolute reliability of leg stiffness did decrease with each increase in drop height. This may reflect an increased difficulty in effectively regulating the leg spring under progressively higher braking loads. To our knowledge this is the first study to investigate the reliability of a DJ phase analysis, although similar analytic approaches have been previously used for the countermovement jump. It has been found previously that braking phase variables are less reliable than propulsive phase variables during a countermovement jump in youth athletes [282]. Nonetheless, in more mature youth athletes (i.e. post peak height velocity), eccentric (i.e. braking) force and power has previously demonstrated acceptable reliability (CVs: < 10%) during a countermovement jump [282]. The higher absolute reliability for eccentric phase variables in the present study compared with those previously reported may be related to the differences in SSC type (i.e. fast versus slow), jump type (i.e. DJ versus countermovement jump), training status of the participants (i.e. well trained adult sprint athletes versus youth athletes), and the inclusion of a familiarization session. Indeed, the motor pattern of the eccentric phase of the countermovement jump may be more variable than the concentric phase [282, 299]. It is possible that the smaller hip, knee and ankle joint amplitudes during the DJ in the present study attenuated the braking phase variability associated with larger ranges of motion previously reported. Additionally, the familiarization during the present study may have further refined this braking pattern. In an effort to ensure generalizability of the findings, the present study implemented three standardised bilateral drop heights and therefore braking loads that span the range typically used within research and practice [292, 300-302].

5.5.2 Utility of a DJ phase analysis

The ability to reliably measure reactive strength is of substantial interest to researchers and practitioners assessing athletes in sports where lower limb fast SSC function is

considered a determinant of performance [16, 303, 304]. In addition, it is proposed that determining eccentric and concentric phase contributions to fast SSC function is of additional utility to the assessment and development of athletic performance. Indeed, eccentric muscle function in particular is considered critical in SSC performance during high force locomotive tasks [1]. Previous research has reported that performance outcomes such as jump height may not comprehensively describe the nature of underlying MTU function during slow and fast SSC movements [65, 305]. It has also been found that training-induced enhancements in countermovement jump performance may be largely related to improvements in eccentric power [65], while eccentric velocity has been shown to be an important factor alongside take-off velocity underpinning higher jump heights achieved during a 0.45m DJ in elite versus sub-elite sprinters [305]. Although it appears that reactive strength can improve with training in recreationally trained participants [302], and reactively trained athletes [304], less is known about how changes in eccentric and concentric muscle function influence performance. Therefore, it is proposed that the use of braking and propulsive phase kinetic variables to infer eccentric and concentric MTU function during a DJ is of substantial utility in identifying the determinants of reactive strength and therefore fast SSC function.

5.5.3 Limitations

It should be acknowledged that there are several limitations with the present protocol. While the use of a single force platform allows the determination of performance measures (i.e. contact time, flight time and RSI) and vertical ground reaction forces (i.e. kinetic variables) in a practical setting, it does not assess the role of joint kinematics in DJ performance. As such this methodology does not identify the relative kinetic and kinematic contribution of individual joints (i.e. hip, knee and ankle) to DJ performance. Furthermore, leg stiffness is modelled using a method based upon ground contact time and flight time rather than directly measuring changes in leg length (i.e. deformation) when exposed to a given vertical force. It should also be acknowledged that there were likely small differences between expected and resultant drop heights due to differences in stepping technique. Nonetheless, the high absolute reliability of braking impulse (CV: 2.2-3.0%) would indicate that stepping technique remained consistent across trials.

Finally, an important limitation and consideration for subsequent research is the lack of *in vivo* measurement of eccentric or concentric MTU behaviour. We are assuming that braking and propulsive phase kinetic variables reflect underlying eccentric and concentric phase MTU behaviour within a SSC (e.g. braking force reflects a more forceful eccentric contraction). Nonetheless, previous research has identified this MTU behaviour under equivalent high force fast SSC conditions [9, 11, 12], and therefore we believe this assumption is warranted.

5.6 Conclusion

The present data indicate that bilateral DJ performance and underlying braking and propulsive phase kinetic variables can be reliably assessed from a range of heights between 0.25m and 0.75m. With the exception of leg stiffness, drop height did not seem to have any additional effect on this variability during bilateral DJs. A DJ phase analysis is a reliable method of assessing reactive strength and kinetic determinants in trained athletes. It is proposed that braking and propulsive phase kinetic variables can be used to provide insight into eccentric and concentric muscle function under fast SSC conditions.

The Kinetic Determinants of Reactive Strength in Highly Trained Sprint Athletes

6.0 Lead Summary

The previous chapter identified that a DJ phase analysis can reliably determine braking and propulsive phase kinetic variables underpinning reactive strength in trained athletes. It is proposed that this kinetic information provides insight into eccentric and concentric muscle function under fast SSC conditions, and subsequently, the ability to effectively regulate leg spring stiffness when exposed to large braking forces. Fast SSC function is of substantial importance to high force locomotive tasks such as sprint running, and the ability to assess and develop it has implications for athletic performance such as sprinting. It is believed that eccentric muscle function is an integral determinant of fast SSC performance. However, there is little available data supporting this proposition in highly trained athletes completing a high force fast SSC task. As noted previously, fast SSC function is typically inferred from assessments of reactive strength. Identifying the role of braking and propulsive phase kinetic variables in well-developed reactive strength is proposed to provide insight into the relative role of eccentric and concentric muscle function in fast SSC performance. Therefore, the purpose of this study was to determine the braking and propulsive phase kinetic variables underpinning reactive strength in highly trained sprint athletes in comparison to a non-sprint trained control group. Twelve highly trained sprint athletes and twelve non-sprint trained participants performed DJs from 0.25m, 0.50m and 0.75m onto a force platform. One familiarization session was followed by an experimental testing session within the same week. RSI, contact time, flight time, and leg stiffness were determined. Kinetic variables including force, power and impulse were assessed within the braking and propulsive phases. Trained sprint athletes demonstrated higher RSI versus non-sprint trained participants across all drop heights (ES ±90% CL: 3.11 ±0.86). This difference was primarily attained by briefer contact times (ES: -1.49 ±0.53) with smaller differences observed for flight time (ES: 0.53 ±0.58). Leg stiffness, braking and propulsive phase force and power were higher in trained sprint athletes. Very large differences were observed in mean braking force (ES: 2.57 ±0.73) which was closely associated with contact time (r = -0.93). Trained sprint athletes exhibited superior reactive strength than non-sprint trained participants. This was due to the ability to strike the ground with a stiffer leg spring, an enhanced expression of braking force, and possibly an increased utilization of elastic structures. Therefore, these data support the proposition that high force fast SSC

performance in trained athletes is largely determined by a short and forceful eccentric muscle action.

6.1 Introduction

Track and field sprint athletes require a number of well-developed physical qualities to be competitive in their respective events. Faster sprinters appear to attain higher top speeds by applying greater mass-specific forces during a briefer ground contact phase than slower sprinters [20, 21]. Furthermore, in a cohort of elite, sub-elite and non-sprinters it has been shown that faster top speeds are attained via the application of greater relative vertical forces in the first half (i.e. braking and early propulsive phase) of ground contact [21]. It is not clear what mechanism(s) underpin this force-time waveform. However, it may be speculated that elite sprinters are better able to strike the ground with a stiffer leg spring which increases vertical ground reaction forces, the utilization of MTU elastic elements, and subsequently, the attainment of higher running speeds [6, 7, 21]. The ability to rapidly absorb high braking, or eccentric, forces and subsequently produce a high propulsive, or concentric, force within a SSC is referred to as reactive strength [296]. Lower limb leg spring stiffness and reactive strength qualities may underpin the expression of high mass-specific ground reaction forces attained by faster sprint athletes at maximum velocities. Unfortunately, the measurement of ground reaction forces during maximum velocity sprinting requires extensive equipment and remains inaccessible to most as a profiling tool. Therefore, more readily implementable field based measures have been utilized to assess the reactive capabilities of the lower limb within athletic profiling.

The DJ is used as an assessment of reactive strength of the hip, knee and ankle extensors [81, 306] and serves as a relatively specific assessment of reactive strength relevant to sprinting performance [305, 307, 308]. Large associations have been found (i.e. $r = 0.62$-0.74) between the moments of the knee and ankle during a rebound jump (similar to a DJ) and those attained during sprinting in track athletes [309]. Typically ground contact time and jump height (or flight time) are selected as outcome measures from each jump, while a RSI can be determined by dividing the jump height, or flight time, by the ground contact time [306]. Furthermore, a range of drop heights are commonly used and the height at which a peak RSI is elicited is reported; a higher optimal drop height is considered to reflect an increased capability to tolerate braking forces [17]. Trained athletes have been demonstrated to have both higher RSI scores from a given drop height, and a higher optimum drop height than non-athletes [300,

305]. Associations between maximum sprinting velocity, DJ height [308, 310, 311], and RSI [307] have also been reported in sprinters and non-sprint athletes [306, 312]. While the RSI performance measure appears to be of utility, to date no study has investigated the kinetic variables within the distinct braking and propulsive phases of a DJ which would provide more detailed insight into reactive strength qualities than RSI alone. This kinetic information might additionally provide a link between a commonly used reactive strength assessment and the ability to attain the idiosyncratic force-time waveform expressed in elite sprint athletes at maximum velocity.

It was proposed that trained sprint athletes would exhibit a higher DJ RSI across three progressively higher drop heights (i.e. braking loads) than non-sprint trained individuals; this difference would be due to the ability to produce higher vertical ground reaction forces in a briefer ground contact phase. Furthermore, it was believed that sprint trained athletes would have a superior ability to strike the ground with a stiffer leg spring which would be reflected in the underlying braking phase kinetic variables. Finally, this study sought to determine differences between the intended drop height (i.e. box height) and predicted drop height using force-time data and the impulse-momentum principle. It was proposed that there would be small differences between intended and predicted drop heights across both subject cohorts.

6.2 Methods

6.2.1 Experimental overview

A cross-sectional design was used and a cohort of highly trained track and field sprinters were compared against a non-sprint trained control group. Subjects performed DJs onto a force platform from three box heights of 0.25m, 0.50m and 0.75m which resulted in predicted drop heights of 0.21 ± 0.02m, 0.41 ± 0.03m, and 0.58 ± 0.06m. The box heights and subsequent predicted drop heights were chosen to reflect the range of braking loads typically reported within research and practice [313, 314]. The RSI performance measure was determined via contact time and flight time. Braking and propulsive kinetic variables were determined via force-time data to provide additional insight into reactive strength performance. Participants completed one descriptive

information and familiarization session followed by one experimental trial session. Familiarization and trial sessions were separated by a minimum of 24 hours and a maximum of 48 hours, performed at approximately the same time of day (i.e. ± 2 hours), and within the same strength and conditioning laboratory.

6.2.2 Subjects

A total of 24 subjects were recruited to participate in the study, including 12 highly trained track and field sprint athletes and 12 non-sprint trained individuals (Table 6.1). All trained sprint athletes had represented New Zealand in international competition and were classified based on personal bests within their given event using the IAAF scoring tables [315], and were attained within 1.3 ± 1.6 y of the testing period. Of the 12 trained sprint athletes, 5 participated primarily in the 100m and 200m sprints, 4 participated in the 400m sprint, and 3 participated in either the heptathlon or decathlon. Non-sprint trained participants were physically active (i.e. participated in recreational sport or exercise at least three times per week for at least 1 year) but had no formal sprint training experience. All participants were free of injury or illness which could affect jumping performance at the time of testing. Informed consent was completed and all testing protocols complied with AUT ethical guidelines. All testing protocols were approved by the University Ethics Committee.

Table 6.1. Descriptive information for non-sprint trained participants ($n = 12$) and trained sprint athletes ($n = 12$).

Variable	Non-Sprint Trained (7m, 5f)	Trained Sprint (7m, 5f)	ES (±90%CI)
Age (y)	26 ± 3	24 ± 6	-0.64 ±1.01
Body Mass (kg)	73 ± 11	73 ± 10	-0.01 ±0.62
Height (cm)	173 ± 8	178 ± 9	0.50 ±0.72
IAAF Points	NA	1035 ± 71	-

Abbreviations: CL: confidence limits; cm: centimetres; ES: effect size; f: females; IAAF: International Association of Athletics Federations; kg: kilograms; m: males; y: years. * 1035 IAAF points is approximately equivalent to 100m performances of 10.51s and 11.87s for males and females, respectively.

6.2.3 Familiarization

During the familiarization session participants were provided with an overview of all study procedures, were screened for any contraindications to exercise and gave informed consent. Height (m) and body mass (kg) were then recorded. Participants were then familiarized with the DJ protocol at all drop heights.

6.2.4 Drop jump protocol

A general warm up was completed consisting of 3-minutes light exercise on a stationary cycle ergometer (95C Lifecycle, Life Fitness, Hamilton, New Zealand), followed by 5-minutes of dynamic mobility and callisthenic exercises addressing the lower limb musculature to be assessed (i.e. hip, knee & ankle extensors). The DJ assessment was completed bilaterally from three box heights (0.25m, 0.50m and 0.75m), which resulted in a predicted drop height of the centre of mass of 0.21 ± 0.02m, 0.41 ± 0.03m, and 0.58 ± 0.06m after accounting for technique in stepping from the box (see Results). Participants completed one practice jump for each condition followed by three maximal attempts (i.e. 12 bilateral jumps in total) with 30-seconds of recovery between each trial and 60-seconds between each height. The three maximal attempts were averaged and used for data analysis. Participants were instructed to perform the DJs with hands akimbo, and to step forward from the box. They were explicitly asked to simultaneously attempt to minimize their ground contact time while maximizing their jump height, but to prioritize a brief ground contact time [293]. Trials in which technique was notably compromised were excluded and repeated. DJs were performed from a plyometric box onto an AMTI force platform sampling at 1000 Hz (AMTI, Watertown, MA, USA). A custom-designed LabView (National Instruments; version 8.2, Austin, TX, USA) program was used to collect and analyse the data.

6.2.5 Data analysis

A fourth-order Butterworth low-pass filter with a cut-off frequency of 200 Hz was used to smooth all force-time data. A vertical force threshold of 30 N was used to establish

zero force and remove noise of the unweighted platform. The deviation from zero force was used to demarcate the beginning and end of the ground contact phase, and the end of the flight phase. Flight time was used to estimate vertical take-off velocity of the centre of mass. From which the change in velocity and body mass was then used to estimate the propulsive impulse. Braking impulse was determined via the subtraction of the propulsive impulse from the net or total impulse measured during the ground contact phase as derived from the force-time curve. The time point marking the transition from braking to propulsive impulse within the contact phase was calculated by the summation of fractional (sample by sample) impulse from the point of initial contact to when the sum was equal to the prior calculated negative or breaking impulse. This time point was used to define the braking and propulsive phases. From braking impulse and body mass the estimated landing velocity and drop height of the centre of mass were calculated. Acceleration of the centre of mass for the DJ was determined via the division of the measured force by known body mass and velocity was then determined via the integration of the acceleration data. Power was then calculated from the force and velocity data. Force- and power-time data parameters of interest were phase duration (s), peak and mean force ($N \cdot kg^{-1}$), peak and mean power ($W \cdot kg^{-1}$), and impulse ($N \cdot s^{-1} \cdot kg^{-1}$) within the braking and propulsive phases. Braking impulse was also used to estimate landing velocity and therefore predicted drop height in comparison to the intended drop height (i.e. actual box height) to account for differences in stepping technique. Contact time (s), flight time (s), and RSI (flight time divided by contact time) were also determined. Leg spring stiffness ($kN \cdot m \cdot kg^{-1}$) was calculated for each DJ using a method described previously [297]:

$$K_{Leg} = \frac{M \cdot \pi (T_f + T_c)}{T_c^2 \left(\frac{T_f + T_c}{\pi} - \frac{T_c}{4} \right)} \qquad (\text{in } N \cdot m^{-1})$$

Where M is total body mass, T_c is contact time, and T_f is flight time. This value was subsequently converted from $N \cdot m^{-1}$ to $kN \cdot m^{-1}$ and divided by body mass. We have previously found (Chapter 5) all the above variables assessed to exhibit acceptable inter-session reliability from each drop height (CV: 2.4-11.0%, ICC: 0.66-0.97).

6.3 Statistical Analysis

Means and SDs were calculated. ES statistics were determined to establish the magnitude of any observed effects between trained sprint and non-sprint trained participants [280]. A statistical spreadsheet was used to calculate standardised differences (i.e. Cohen's *d*), or ES (with 90 % CIs and CLs) using the pooled SD [279]. ESs were used to compare differences within, and between, trained sprint and non-sprint trained groups across the three drop heights. The smallest worthwhile change or difference was calculated as 0.2 multiplied by the between subject SD [279]. Threshold values for ES statistics were set as: ≤ 0.2 trivial/unclear, > 0.2 small, > 0.6 moderate, > 1.2 large, > 2.0 very large, and > 4.0 extremely large [280]. Pearson Product-Moment Correlations was calculated for selected variables of interest. The magnitude of the correlation between variables was determined via the following criteria: ≤ 0.1 trivial, > 0.1-0.3 small, > 0.3-0.5 moderate, > 0.5-0.7 large, > 0.7-0.9 very large, and > 0.9-1.0 almost perfect [280].

6.4 Results

6.4.1 Effect of training status on DJ performance

Differences in DJ performance measures across each drop height between trained sprint and non-sprint trained participants are reported in Figure 6.1. Very large differences in RSI were observed between trained sprint athletes and non-sprint trained participants at all drop heights (ES ±90% CL: 3.64 ±0.90, 2.65 ±0.80, and 2.56 ±0.81, for 0.25m, 0.50m, and 0.75m, respectively). These differences were underpinned by shorter contact times (large differences) at all heights (ES: -1.49 ±0.53, -1.29 ±0.53, and -1.32 ±0.52, for 0.25m, 0.50m, and 0.75m, respectively), and longer flight times (moderate differences) at 0.50m and 0.75m (ES: 0.60 ±0.58, and 0.65 ±0.56, for 0.50m, and 0.75m, respectively). No differences in flight time were found at 0.25m. Trained sprinters exhibited higher leg stiffness (large differences) compared with non-sprint trained participants at all heights (ES: 1.94 ±0.69, 1.61 ±0.67, and 1.80 ±0.73, for 0.25m, 0.50m, and 0.75m, respectively).
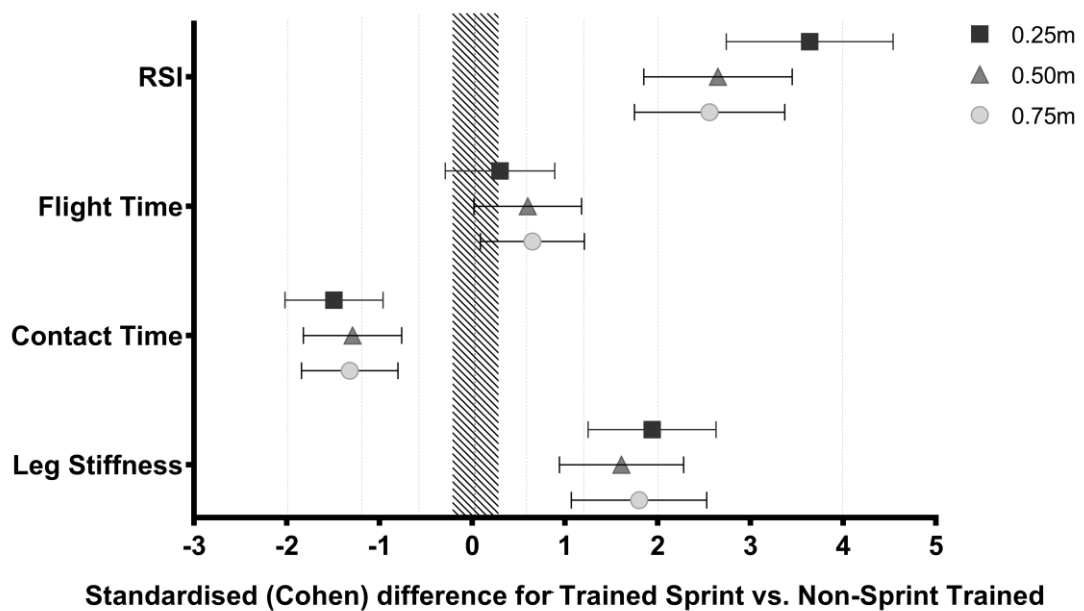
Figure 6.1. The standardised (Cohen) difference for trained sprint athletes (*n* = 12) versus non-sprint trained participants (*n* = 12). Differences are for the reactive strength index (RSI), flight time, contact time and leg stiffness for drop jumps performed from three drop heights (0.25m, 0.50m and 0.75m). *Error bars* indicate uncertainty in the true mean changes with 90 % confidence intervals. The *shaded area* represents the smallest worthwhile change.

6.4.2 Effect of training status on DJ kinetic variables

Differences in the kinetic variables underpinning DJ performance across each drop height between trained sprint and non-sprint trained participants are reported in Figure 6.2. Moderate to very large differences were observed for both peak and mean force within braking and propulsive phases across all drop heights between trained sprint and non-sprint trained participants. There were moderate to very large differences between trained sprint and non-sprint trained participants in peak and mean power within braking and propulsive phases from all drop heights. Moderate to large differences in braking and propulsive phase durations were demonstrated between groups. Aligning with differences in contact time, phase durations were shorter in trained sprint athletes. The differences in phase duration attenuated the magnitude of differences between groups in impulse, although a small difference in braking impulse was evident at 0.25m, and small and moderate differences were found in propulsive impulse at 0.50m, and

0.75m, respectively. Almost perfect correlations between contact time and mean braking force were found from heights of 0.50m (r = -0.92; r^2 = 0.84) and 0.75m (r = -0.93; r^2 = 0.87) while a very large correlation (r = -0.87; r^2 = 0.76) was demonstrated from 0.25m (Figure 6.3).
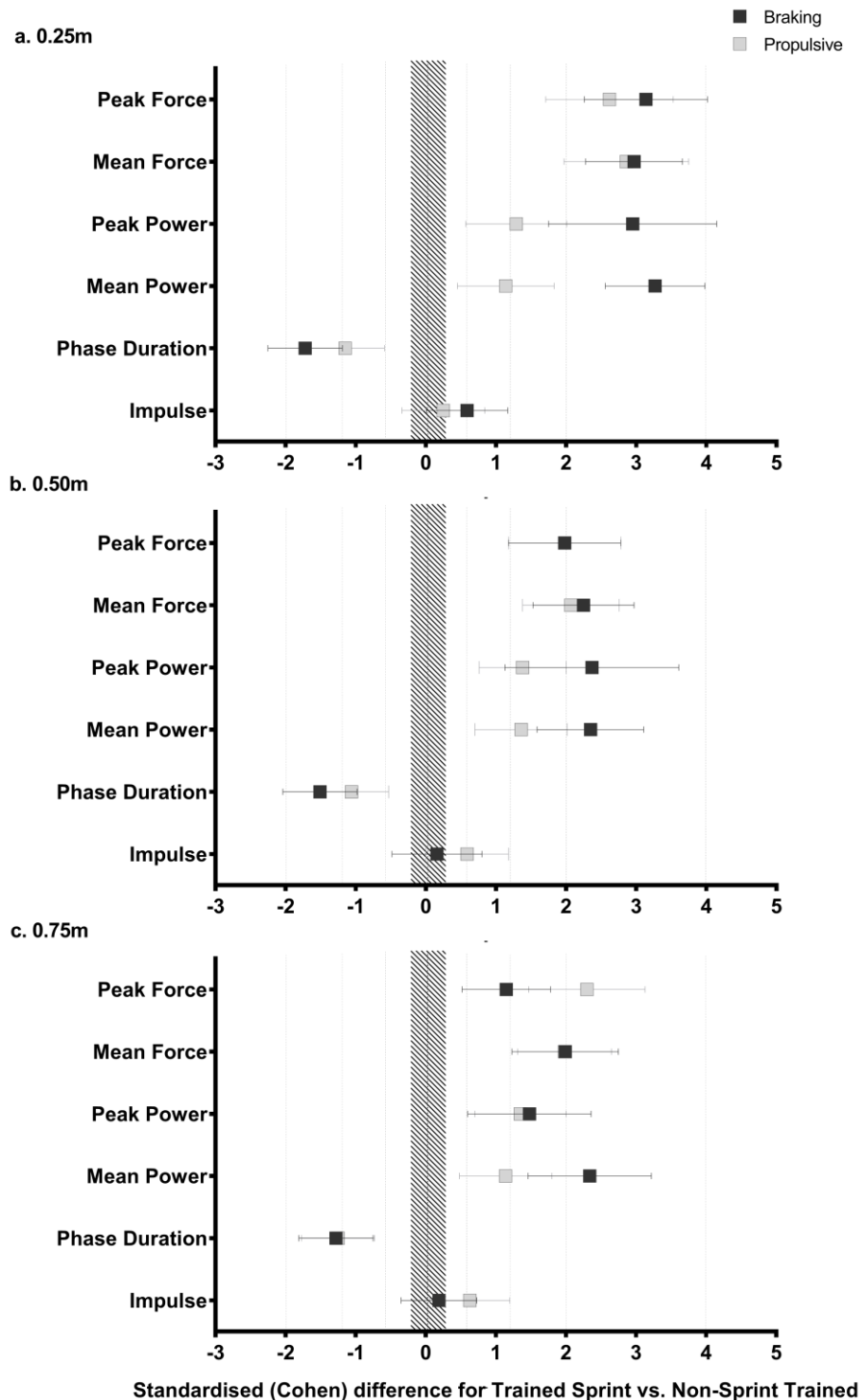
Figure 6.2. The standardised (Cohen) difference for trained sprint athletes ($n = 12$) versus non-sprint trained participants ($n = 12$). Differences are for braking and propulsive phase kinetic variables determined from drop jumps performed from a. 0.25m, b. 0.50m, and c. 0.75m. *Error bars* indicate uncertainty in the true mean changes with 90 % confidence intervals. The *shaded area* represents the smallest worthwhile change.
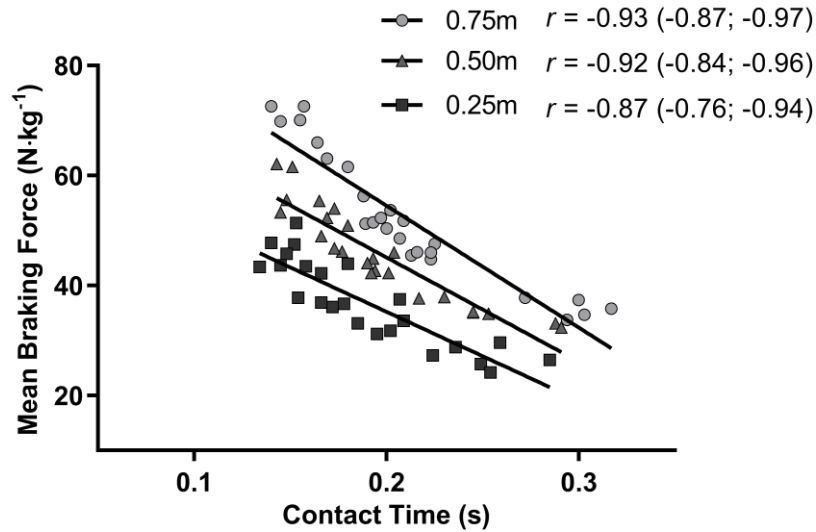
Figure 6.3. Relationship between contact time (s) and mean braking force (N·kg^{-1}) during drop jumps from 0.25m, 0.50m and 0.75m for all participants ($n = 24$).

6.4.3 Effect of drop height

Performance variables from each DJ height are reported in Table 6.2 for both non-sprint trained participants and trained sprint athletes. No changes in RSI were observed for either group from 0.25m to 0.50m, while the increase from 0.50m to 0.75m resulted in moderate, and small, decreases in RSI in non-sprint trained (ES: -0.71 ±0.45) and trained sprint (ES: -0.43 ±0.17) groups, respectively. The increase in drop height from 0.25m to 0.50m resulted in a small increase in contact time for the trained sprint group (ES: 0.44 ±0.25), while the increase from 0.50m to 0.75m elicited a small increase in contact time for both groups (ES: 0.54 ±0.36, and 0.55 ±0.26, for non-sprint trained and trained sprint, respectively). Drop height did not influence DJ flight time (and therefore jump height) in non-sprint trained participants, while a small increase was observed in trained sprint athletes from 0.25m to 0.50m (ES: 0.39 ±0.13). A small decrease in leg stiffness was found from 0.50m to 0.75m in non-sprint trained participants (ES: -0.40 ±0.23), and with both height increments in trained sprint athletes (ES: -0.48 ±0.23, and -0.43 ± 0.20, respectively). With each increase in drop height moderate to very large increases in peak, and mean, braking forces were observed for both groups (Table 6.2). Similarly, there were very large to extremely large increases in peak, and mean, braking

power, and braking impulse in both groups. Moderate and small reductions in peak propulsive force were observed from 0.50m to 0.75m for non-sprint trained and trained sprint groups, respectively. Mean propulsive force exhibited small and moderate reductions from both increments in non-sprint trained participants, while a small reduction was observed from 0.50m to 0.75m in trained sprint athletes. A small decrease in peak propulsive power occurred from 0.25m to 0.50m non-sprint trained participants, with a small increase observed in trained sprint athletes. A small decrease in peak propulsive power 0.50m to 0.75m was found in trained sprint athletes, with no change observed in non-sprint trained participants. Trained sprint athletes exhibited a small increase in mean propulsive power from 0.25m to 0.50m, while a small decrease in mean propulsive power occurred 0.50m to 0.75m in both groups. Trained sprint athletes exhibited a small increase in propulsive impulse from 0.25m to 0.50m.

6.4.4 Predicted drop height versus box height

There were similar differences between the predicted drop heights determined via the impulse momentum principle and the box heights of 0.25, 0.50m and 0.75m across both groups. The predicted drop height was lower for both non-sprint trained and trained sprint groups from 0.25m (0.21 ± 0.02 vs. 0.21 ± 0.01; ES ±90% CL: 0.13 ±0.59), 0.50m (0.40 ± 0.03 vs. 0.41 ± 0.03; ES ±90% CL: 0.17 ±0.66) and 0.75m (0.58 ± 0.05 vs. 0.57 ± 0.06; ES ±90% CL: 0.28 ±0.57).

Table 6.2. A comparison of kinetic variables underpinning drop jump performance across three drop heights (0.25m, 0.50m and 0.75m) for non-sprint trained participants (*n* = 12) and trained sprint athletes (*n* = 12). Performance and kinetic data presented as means and standard deviations (±SD), effect size statistics between drop heights presented as the standardised (Cohen) difference and 90% confidence intervals (90% CI).

	Non-Sprint Trained (± SD)			Effect Size (90% CI)		Trained Sprint (± SD)			Effect Size (90% CI)	
	0.25m	0.50m	0.75m	0.50m vs. 0.25m	0.75m vs. 0.50m	0.25m	0.50m	0.75m	0.50m vs. 0.25m	0.75m vs. 0.50m
RSI (s·s⁻¹)	2.11 ± 0.25	2.07 ± 0.36	1.88 ± 0.37	-0.18 (-0.56; 0.21)	-0.71 ** (-1.16; -0.26)	3.08 ± 0.40	3.08 ± 0.50	2.90 ± 0.53	0.00 (-0.28; 0.29)	-0.43 * (-0.60; -0.27)
Contact Time (s)	0.22 ± 0.04	0.23 ± 0.04	0.25 ± 0.05	0.14 (-0.13; 0.40)	0.54 * (0.18; 0.90)	0.16 ± 0.02	0.17 ± 0.02	0.18 ± 0.02	0.44 * (0.19; 0.69)	0.55 * (0.29; 0.81)
Flight Time (s)	0.46 ± 0.08	0.46 ± 0.09	0.45 ± 0.09	-0.03 (-0.18; 0.13)	-0.06 (-0.18; 0.07)	0.49 ± 0.07	0.52 ± 0.07	0.51 ± 0.06	0.39 * (0.26; 0.52)	-0.02 (-0.16; 0.12)
Leg Stiffness (kN·m·kg⁻¹)	0.30 ± 0.10	0.29 ± 0.09	0.24 ± 0.08	-0.11 (-0.31; 0.10)	-0.40 * (-0.63; -0.16)	0.50 ± 0.10	0.44 ± 0.10	0.40 ± 0.10	-0.48 * (-0.70; -0.25)	-0.43 * (-0.63; -0.23)
Braking Phase Variables										
Braking Phase Duration (s)	0.10 ± 0.02	0.10 ± 0.02	0.10 ± 0.02	0.04 (-0.24; 0.31)	0.24 * (-0.10; 0.59)	0.06 ± 0.01	0.07 ± 0.01	0.07 ± 0.01	0.53 * (0.15; 0.90)	0.33 * (-0.01; 0.68)
Braking Peak Force (N·kg⁻¹)	49 ± 8	69 ± 16	92 ± 20	2.39 †† (1.68; 3.10)	2.78 †† (2.14; 3.42)	75 ± 12	95 ± 19	116 ± 18	1.49 † (1.13; 1.85)	1.58 † (1.23; 1.93)
Braking Mean Force (N·kg⁻¹)	30 ± 4	39 ± 5	43 ± 7	2.01 †† (1.61; 2.41)	0.96 ** (0.47; 1.46)	43 ± 4	52 ± 6	59 ± 9	1.80 † (1.31; 2.29)	1.42 † (0.88; 1.96)
Braking Peak Power (W·kg⁻¹)	-80 ± 12	-147 ± 21	-241 ± 29	5.03 Ω (4.29; 5.76)	7.08 Ω (6.32; 7.85)	-119 ± 29	-201 ± 51	-287 ± 47	2.64 †† (2.16; 3.11)	2.81 †† (2.30; 3.32)
Braking Mean Power (W·kg⁻¹)	-42 ± 4	-65 ± 9	-78 ± 14	5.07 Ω (4.33; 5.82)	3.00 †† (1.87; 4.13)	-56 ± 5	-87 ± 11	-112 ± 22	5.83 Ω (5.02; 6.64)	4.89 Ω (3.54; 6.24)
Braking Impulse (N·s·kg⁻¹)	1.94 ± 0.17	2.79 ± 0.12	3.31 ± 0.23	4.69 Ω (4.33; 5.05)	2.91 †† (2.51; 3.31)	2.05 ± 0.12	2.81 ± 0.11	3.36 ± 0.13	5.69 Ω (5.36; 6.01)	4.12 Ω (3.68; 4.57)
Propulsive Phase Variables										
Propulsive Phase Duration (s)	0.12 ± 0.02	0.13 ± 0.02	0.14 ± 0.03	0.22 * (-0.03; 0.47)	0.78 ** (0.37; 1.18)	0.10 ± 0.01	0.10 ± 0.01	0.11 ± 0.01	0.27 * (0.06; 0.49)	0.58 * (0.36; 0.81)
Propulsive Peak Force (N·kg⁻¹)	45 ± 5	44 ± 8	40 ± 6	-0.04 (-0.53; 0.45)	-0.74 ** (-1.12; -0.36)	60 ± 9	60 ± 11	56 ± 9	0.08 (-0.32; 0.48)	-0.51 * (-0.76; -0.25)
Propulsive Mean Force (N·kg⁻¹)	29 ± 2	28 ± 3	26 ± 3	-0.27 * (-0.67; 0.13)	-0.96 ** (-1.46; -0.46)	35 ± 3	35 ± 4	33 ± 4	0.14 (-0.10; 0.38)	-0.54 * (-0.71; -0.38)
Propulsive Peak Power (W·kg⁻¹)	58 ± 11	55 ± 16	53 ± 13	-0.28 * (-0.65; 0.09)	-0.14 (-0.58; 0.29)	73 ± 13	79 ± 15	72 ± 13	0.39 * (-0.01; 0.78)	-0.46 * (-0.76; -0.15)
Propulsive Mean Power (W·kg⁻¹)	34 ± 8	33 ± 8	31 ± 8	-0.09 (-0.35; 0.17)	-0.23 * (-0.47; 0.01)	43 ± 9	45 ± 8	40 ± 8	0.20 * (-0.09; 0.48)	-0.48 * (-0.80; -0.15)
Propulsive Impulse (N·s·kg⁻¹)	2.27 ± 0.40	2.26 ± 0.42	2.25 ± 0.41	-0.02 (-0.17; 0.13)	-0.03 (-0.15; 0.10)	2.38 ± 0.33	2.52 ± 0.32	2.53 ± 0.29	0.42 * (0.28; 0.55)	0.01 (-0.14; 0.15)

Abbreviations: CI: confidence interval; cm; centimetres; kN·m·kg⁻¹: kilonewtons per metre per kilogram; m: metre; N·kg⁻¹: Newtons per kilogram; N·s·kg⁻¹: Newtons per second per kilogram; RSI: reactive strength index; s: seconds; SD: standard deviation; W·kg⁻¹: watts per kilogram; *: small difference; **: moderate difference; †: large difference, ††: very large difference; Ω: extremely large difference.

6.5 Discussion

This study sought to determine differences in reactive strength and underpinning kinetic variables during the DJ between highly trained sprint athletes and a non-sprint trained control group. It has previously been shown that the DJ RSI can discriminate elite sprint athletes [305], but this is the first study to demonstrate that the superior RSI exhibited by trained sprint athletes is determined primarily by large differences in contact time (Figure 6.1). Moderate differences were found in flight time (and therefore jump height) at the two highest drop heights, but no differences were seen from the lowest drop height. This briefer ground contact phase was determined primarily by the expression of high relative braking forces (Figure 6.3). Previous research has identified that the ground contact force-time waveform produced by elite sprinters at maximum velocity is characterised by a shorter and more forceful braking phase [21]. The present kinetic data provide evidence for a similar mechanism occurring during the DJ across three progressively higher braking loads and therefore support the utility of the DJ as an assessment tool for sprint athletes.

Kinetic variables expressed during a reactive jump are associated with those observed during maximum velocity sprinting [309], and therefore the DJ phase analysis is proposed to provide insight into reactive strength capabilities expressed during sprinting. It should be acknowledged that qualitatively the shape of the force-time waveform did not appear to be influenced by training status (Figure 6.4), rather the magnitude and rate of force application were the distinguishing features. Both braking and propulsive phases were shorter and more forceful than non-sprint trained participants during a DJ from various heights in the trained sprint cohort. As indicated by the large differences in leg stiffness at all heights, trained sprinters were better able to stiffen the leg spring upon ground contact which enabled a short and forceful ground contact phase. All participants attempted to minimize ground contact time, which indicates that non-sprint trained individuals may not have the neuromuscular capabilities necessary to rapidly absorb and return high braking forces. This proposition is supported by the larger effect of training status on braking versus propulsive power (Figure 6.2). Furthermore, when all participants were pooled approximately 76-87% of the variance associated with contact time from all drop heights was explained by mean braking force (Figure 6.3).
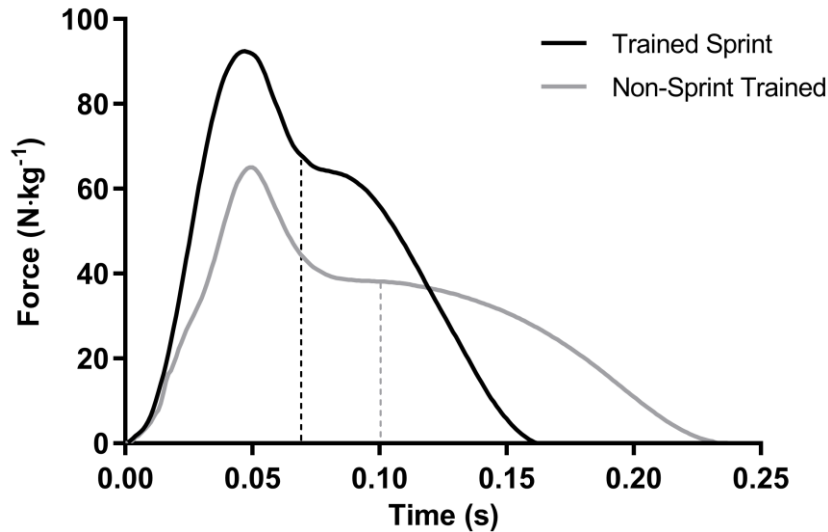
Figure 6.4. Representative force-time curve during the ground contact phase of a drop jump from 0.50m for a trained sprint athlete (solid black line) and a non-sprint trained participant (solid grey line). Dashed vertical lines represent the transition from braking to propulsive phases.

Stiffness regulation is proposed to play an integral role in the braking phase of fast SSC movements [14]. A stiffer leg spring has been shown to acutely modulate ground contact times during hopping [7], and is associated with stride frequency [316], and maximum velocity sprint performance in athletic populations [7]. Therefore, mechanisms underpinning higher leg spring stiffness are likely responsible for the rapid ground contact times in sprint trained athletes. Net joint stiffness (e.g. of the ankle, knee and hip) is proposed to be a function of feed-forward pre-activation of the agonist and antagonist muscles surrounding the joint [317], short latency stretch reflex activation [318], and possibly an MTU that has the necessary intrinsic stiffness characteristics for rapid force application [319]. While muscle activation was not measured it is proposed that the trained sprinters implemented a superior motor strategy involving pre-activation and a stronger eccentric quasi-isometric muscle contraction on ground contact due to an increased reflex potentiation of muscle excitability [304]. The stiffening of the leg spring allowed the expression of high braking forces, the absorption of work/energy by biological structures, and a more forceful propulsive phase, resulting in briefer ground contact times during the DJs by trained sprint athletes compared to the non-sprint trained group.

In addition to enhanced stiffness regulation, the trained sprinters' ability to apply more force in less time compared with non-sprint trained participants may also be related to differences in neuromuscular function and MTU properties. Relative strength has been found to be related to RSI in collegiate athletes [320], however this was primarily due to associations with jump height, not contact time. The contact times reported in these 'strong' collegiate athletes from drop heights of 0.30-0.60m (i.e. contact times of 0.21-0.23s) were closer to those attained by the non-sprint trained control participants in the present study. It is possible that a threshold of muscle strength is necessary to attain a particular jump height but may have little influence on contact time and the ability to rapidly apply a given relative force. Indeed, while maximal force production capabilities are crucial to an absolute RFD, the time to reach a given force relative to maximal force capabilities may be more related to motor unit firing rate (and therefore muscle activation), muscle fibre composition and MTU stiffness [271]. Previous research has found that intrinsic MTU stiffness can increase with reactive training [321], which may augment the storage and return of elastic energy while attenuating the electromechanical delay for rapid force transmission throughout the MTU [271]. Furthermore, trained sprinters are likely to express a faster phenotype (i.e. larger relative area of type II fibres and longer muscle fascicle lengths) [322, 323] which would aid RFD and power output [271]. Unfortunately, MTU structure and composition was not measured and therefore the influence of these factors on the present findings remain unclear. Although participants were familiarised with the protocol and explicitly instructed to minimise ground contact times, the role of differences in DJ technique cannot be entirely ruled out in explaining the magnitude of differences observed between the groups. It should be noted that there was an effect of dropping technique with each increase in box height. Even with explicit instructions and feedback, participants consistently modified their stepping technique with increasing box height which resulted in a discrepancy of approximately 0.04m, 0.09m and 0.17m from 0.25m, 0.50m and 0.75m respectively. This progressive discrepancy was observed irrespective of training status and possibly reflects an unconscious protective adjustment in technique to minimize braking loads.

The increase in drop height and therefore braking force had a clear effect on performance and kinetic variables, however, similar effects were observed for both groups. Contact times were extended as drop height increased, although no obvious inhibition of flight time was observed. The large increases in braking forces with drop

height reflect the additional acceleration of the body mass due to gravity. Longer ground contact times, impaired leg stiffness and lower propulsive force production from 0.75m likely reflect a protective inhibition of muscle activation via reduced Ia afferent input from muscle spindles and/or Golgi tendon organ inhibition [14], and therefore a dampening of the leg spring. An inhibition of muscle activation is typically observed with excessive stretch (i.e. braking) loads [4], and it has previously been demonstrated that Hoffman reflex (H-reflex) amplitude, a measure of motor neuron excitability, is impaired at 0.76m versus 0.31m [292].

Highly trained sprint athletes appear to implement a motor strategy that allows them to strike the ground with a stiffer leg spring, and subsequently, exhibit a more rapid and forceful ground contact phase during DJs than non-sprint trained participants from a range of drop heights. The higher RSI found in trained sprinters was primarily attained by a briefer ground contact time rather than a longer flight time. Trained sprint athletes exhibited superior force and power production within both braking and propulsive phases. However, the briefer ground contact time was largely determined by the application of high relative braking forces. It is possible that due to a combination of reactive training and genetic endowment that sprint trained athletes possess the requisite neuromuscular and MTU properties necessary for rapid force production and effective fast SSC function. Future research needs to more directly elucidate how the kinetic variables underpinning DJ performance translate to the expression of reactive strength during athletic events (e.g. sprinting).

6.6 Practical Applications

The RSI and underpinning kinetic variables effectively discriminate between highly trained sprint athletes and non-sprint trained participants. A higher RSI score may be primarily due to a briefer ground contact time, with a smaller difference observed for flight time. Therefore, it is recommended that in addition to using the RSI as a monitoring tool practitioners should track the constituent contact time and flight time (or jump height) variables. The ability to attain a given flight time or jump height for a briefer contact time may signify a reactive strength improvement relevant to sprint performance. Training methods (e.g. plyometric or eccentric-overload training) that

improve an athlete's capability to strike the ground with a stiffer leg spring and tolerate high braking forces are proposed to maximize reactive strength improvements.

Reactive and Eccentric Strength Contribute to Stiffness Regulation during Maximum Velocity Sprinting in Team Sport Athletes and Highly Trained Sprinters

7.0 Lead Summary

It has been identified in Chapter 6 that the high levels of reactive strength observed in highly trained sprinters are underpinned by the ability to produce more force during a briefer ground contact phase. Reactively strong athletes appear to be better able to strike the ground with a stiffer leg spring and produce large relative braking forces, which in turn, facilitates the attainment of a rapid ground contact phase. It is proposed that these braking phase kinetic characteristics reflect a more effective (i.e. fast and forceful) eccentric muscle action under fast SSC conditions. As noted previously, this mechanism appears to enhance high force fast SSC function and likely has important implications for the performance of athletic tasks such as sprint running. However, there are no data demonstrating the link between eccentric muscle function under fast SSC conditions (i.e. during a reactive strength task) and leg spring stiffness regulation during sprinting. In addition, it is not clear whether high force fast SSC function and leg spring stiffness regulation are a product of maximum eccentric strength *per se*, or the rapid application of sufficient eccentric force under task-specific SSC conditions. Therefore, the purpose of this study was to determine the relationship between lower limb reactive strength, isoinertial eccentric strength, maximum velocity sprint performance and stiffness regulation in team sport athletes compared with highly trained sprinters. Thirteen team sport athletes and eleven highly trained sprinters were recruited. Maximum velocity sprinting speed and underlying kinematic variables were measured. Stiffness regulation at maximum velocity was inferred from modelled vertical and leg stiffness. Reactive strength was determined via the RSI from a 0.50m DJ. An eccentric back squat was used to assess maximum isoinertial eccentric force. Trained sprinters attained a higher maximum velocity (ES ±90% CL: 1.54 ±0.85), briefer contact time (ES: -1.39 ±0.80) and higher vertical stiffness (ES: 1.74 ±0.96) versus team sport athletes. Trained sprinters exhibited a moderately higher RSI (ES: 0.71 ±0.74) via the attainment of a briefer and more forceful ground contact phase. A possible small difference was observed between groups for isoinertial eccentric force (ES: 0.38 ±0.56). RSI demonstrated large to very large associations with maximum velocity ($r = 0.72$) and vertical stiffness ($r = 0.67$). Isoinertial eccentric force was largely correlated with maximum velocity ($r = 0.56$) and RSI ($r = 0.60$), but less so with vertical stiffness ($r = 0.41$). Reactive and eccentric strength contribute to vertical stiffness and maximum velocity sprinting speed in team sport athletes and highly trained sprinters. However,

the stronger association between stiffness regulation at maximum velocity and eccentric muscle function under fast SSC conditions (i.e. DJ mean braking force) compared with maximum isoinertial eccentric strength indicates that fast SSC function and stiffness regulation may be a somewhat task-specific motor strategy.

7.1 Introduction

Sprinting ability is an important component of performance in a range of athletic endeavors [324], and depending upon the distance, may include acceleration, maximum velocity and deceleration phases [18]. While acceleration ability is paramount to sprint performance [324], maximum velocity capabilities are also of substantial interest to team sport and sprint athletes. A very strong association has been demonstrated between maximum velocity and 36.6m sprint time in American football athletes [325]. Furthermore, the relative rate of acceleration remained the same irrespective of sprinting performance, indicating that a higher maximum velocity enabled a superior acceleration performance [325]. Maximum velocity capabilities are of obvious importance to performance in track sprinting with event distances (i.e. 60-400m) allowing the attainment of maximum sprinting speeds. As per other phases of a maximal sprint, maximum velocity is determined by step rate and step length [326]. While there is conjecture (e.g. due to individual variation) as to the relative contribution of these two variables to sprint performance [326, 327], it is clear that improving one or both will increase maximum velocity sprinting speed. Mechanical evidence indicates that faster sprinters attain higher maximum velocities by the application of larger relative vertical ground reaction forces [20, 328], particularly in the first half (i.e. impact phase) of ground contact [21]. Higher vertical forces allow for a briefer ground contact time and higher step rate without compromising vertical impulse necessary to reposition the limbs for subsequent ground contact [20]. Given that time to reposition the limbs does not differ between performance levels [20], reducing ground contact time via increasing vertical forces is therefore the primary means to attaining higher step rates and a faster maximum velocity.

The mechanisms underpinning the attainment of higher vertical forces in faster sprinters have yet to be clearly elucidated. However, technique (i.e. a high knee lift at the end of the swing phase allowing for higher limb velocities immediately preceding touch down) and sufficient stiffness of the lower limb are proposed to be of substantial importance [18, 21]. Indeed, previous research has identified lower limb stiffness to increase in conjunction with sprinting speed [24, 316, 329, 330]. A stiffer leg spring will allow the attainment of higher vertical ground reaction forces [18], facilitate the storage and return of elastic strain energy [6, 21], and increase step rate via a reduction in ground

contact time [24]. Leg stiffness at maximum velocity is largely regulated by the knee joint with a smaller role played by the ankle joint [24, 329]. It has also been demonstrated in well trained sprinters at maximum velocity that positive (i.e. propulsive) work is predominantly generated by the hip and ankle, with the knee serving to prevent the collapse of the limb during weight acceptance of the stance phase [331]. While stiffness of a joint is likely to be influenced by the intrinsic mechanical properties of the MTU, global regulation of the leg spring during maximal velocity sprinting may be predominantly governed by muscle co-contraction [24]. Therefore, stiffness at maximum velocity will likely be influenced by the capability of the knee extensors and ankle plantar flexors to withstand (i.e. to operate quasi-isometrically) large braking or eccentric forces [11, 24]. Requisite reactive strength may therefore be necessary to rapidly absorb and return large vertical ground reaction forces during maximum velocity sprinting. Furthermore, eccentric strength may directly aid lower limb stiffness and reactive strength by preventing excessive lengthening of muscle under high stretch loads, and indirectly by increasing force production during a subsequent quasi-isometric action via residual force enhancement [25] and reflex potentiation [16], thereby maximizing the utilization of elastic structures within the SSC [332]. As it stands, it remains unclear how reactive strength or eccentric strength qualities influence leg spring stiffness regulation during maximum velocity sprinting in trained athletes.

Therefore, the purpose of this study was to investigate the role of lower limb reactive strength, and eccentric strength in stiffness regulation during maximum velocity sprinting in athletes of contrasting sprinting abilities (i.e. team sport athletes compared with highly trained sprinters). Maximum velocity capabilities are highly relevant to team sport athletes and competitive sprinters alike; however, it was proposed that trained sprinters would exhibit superior reactive and eccentric strength qualities to team sport athletes, which in turn would be associated with enhanced stiffness regulation at a higher maximum sprinting velocity. Furthermore, it was thought that due to the specificity of the quality, lower limb reactive strength would exhibit a stronger association with stiffness regulation than eccentric strength.

7.2 Methods

7.2.1 Subjects

A total of 24 participants were recruited to participate in the study, including 13 trained team sport athletes and 11 highly trained track and field sprinters (Table 7.1). All trained sprinters had represented New Zealand in international competition and were classified based on personal bests within their given event using the IAAF scoring tables [315]. This classification was used to provide a representation of performance level as trained sprinters specialised in different track and field events (i.e. 100m, 200m, 400m and Decathlon). Team sport athletes had represented New Zealand in international competition ($n = 8$) or competed regionally ($n = 5$), and were recruited from sports that required the attainment of maximum velocity sprinting speeds in training and competition (i.e. Hockey, Rugby and Soccer). All participants were in their off-season at the time of testing. The focus of training for trained sprinters was general preparation with an emphasis on basic strength. The focus of training for team sport athletes was general preparation with an emphasis on basic strength and aerobic power. All participants were free of injury or illness which could affect performance at the time of testing. Informed consent was completed and all testing protocols complied with AUT ethical guidelines. All testing protocols were approved by the University Ethics Committee.

Table 7.1. Descriptive information for team sport athletes ($n = 13$) and highly trained sprinters ($n = 11$).

Variable	Team Sport (7m, 6f)	Trained Sprint (6m, 5f)	ES (±90% CL)
Age (y)	23 ± 3	23 ± 5	-0.01 ±0.90
Body Mass (kg)	72.8 ± 8.0	73.6 ± 10.2	0.11 ±0.77
Height (cm)	172 ± 4	177 ± 9	1.30 ±1.19 [†]
IAAF Points	NA	1039 ± 59 [*]	-

Abbreviations: CL: confidence limits; cm: centimetres; ES: effect size; f: females; IAAF: international association of athletics federations; kg: kilograms; m: males; y: years; [†]; likely large difference; [*] 1039 IAAF points is approximately equivalent to 100m performances of 10.50s and 11.85s for males and females, respectively.

7.2.2 Experimental overview

Participants reported for one familiarization session and one experimental testing session separated by 5-7 days utilizing a cross-sectional design. During familiarization participants completed informed consent and descriptive information was collected. Participants were familiarized with reactive and eccentric strength protocols. During experimental testing sessions participants completed a maximum velocity sprint assessment followed by reactive and eccentric strength protocols. All testing took place within the same facility at approximately the same time of day.

7.2.3 Maximum velocity sprint assessment

Maximum velocity sprint testing was completed on an indoor track. Following a standardised warm up, participants completed two 50m strides at 80% and 90% of perceived maximum effort followed by two maximal 50m sprints with five minutes' recovery between trials. If requested, participants were given an additional warm up effort before commencing maximal effort trials. Participants began from a split stance with the preferred leg forward and initiated the sprint in their own time. A radar device (Stalker ATS II, Applied Concepts, Dallas, TX, USA) set two metres behind the participant and at the height of the approximate centre of mass (i.e. one metre) was used to capture velocity data at a sampling rate of 46.9 Hz. The radar was operated by a portable laptop using software supplied by the manufacturer (STATS, Applied Concepts, Dallas, TX, USA). Velocity-time data were filtered and clipped at the point of deceleration within the STATS program. Maximum velocity ($m \cdot s^{-1}$) was determined as the highest attained velocity between 35m and 45m for each sprint. A high-speed video camera recording at 300 frames per second was set adjacent to the track at 40m to capture maximum velocity kinematic variables between 35m and 45m. Footage was transferred onto a personal computer and analysed using video analysis software (Kinovea 0.8.15). Contact time (s), flight time (s), step rate (Hz) and step length (m) were averaged across the ten-metre section (i.e. 4-steps per trial). Vertical and leg stiffness ($kN \cdot m \cdot kg^{-1}$) at maximum velocity were modelled using the methods previously described by Morin and colleagues [333]. Vertical stiffness was calculated as the ratio of modelled maximum force over modelled maximum displacement of the centre of

mass, while leg stiffness was calculated as the ratio of modelled maximum force over modelled peak displacement of the leg spring [333]. All variables were determined as the average of the two maximal trials.

7.2.4 Reactive strength assessment

Reactive strength was determined from a DJ performed bilaterally from 0.50m. Based on the findings of chapters 5 and 6, this drop height was chosen as a reliable and optimal drop height to provide a substantial braking load (e.g. a peak braking force of 7-10 x body mass) to be tolerated, without impairing reactive strength. Following a standardised warm up, participants completed one practice jump followed by three maximal attempts with one minute of recovery between trials. Participants were instructed to perform the DJs with hands akimbo, and to step forward from the box avoiding stepping down or jumping up. They were explicitly asked to simultaneously attempt to minimize their ground contact time while maximizing their jump height, but to prioritize a brief ground contact time [293]. Trials in which technique was notably compromised were excluded and repeated. DJs were performed from a plyometric box onto an AMTI force platform sampling at 1000 Hz (AMTI, Watertown, MA, USA). A custom-designed LabView (National Instruments; version 8.2, Austin, TX, USA) program was used to collect and analyse the data. A fourth-order Butterworth low-pass filter with a cut-off frequency of 200 Hz was used to smooth all force-time data. A vertical force threshold of 30 N was used to establish zero force and remove noise of the unweighted platform. The deviation from zero force was used to demarcate the beginning and end of the ground contact phase, and the end of the flight phase. Braking and propulsive phases of ground contact were demarcated using a method described previously [334]. Contact time (s), flight time (s), and RSI (flight time divided by contact time) were determined. Peak and mean force ($N\cdot kg^{-1}$) were determined within the braking and propulsive phases. Leg spring stiffness ($kN\cdot m\cdot kg^{-1}$) was calculated for each DJ using the method of Dalleau and colleagues [297]. All variables were determined as the average of three maximal effort DJs. A pilot investigation (Chapter 5) demonstrated all variables exhibited acceptable inter-session reliability (CV: 3-9%).

7.2.5 Isoinertial eccentric strength assessment

Isoinertial eccentric strength was determined as the mean force produced during an eccentric 1RM back squat to parallel (i.e. a knee angle of 90°). The back squat was performed in a custom-made smith machine (Goldmine, HPSNZ, Auckland, New Zealand) which provided pneumatic assistance during the concentric phase of the movement. Concentric load was therefore limited to ≤ 60kg for all repetitions. Range of motion was individualized using two triggers, one at the top of the movement and one at the bottom the movement (i.e. to initiate the onset of the concentric assistance). Participants were required to descend with the load at a constant velocity for 3-seconds (i.e. approximately 30°/s), feedback was provided by a LPT fitted to the bar sampling at 250 Hz (Goldmine, HPSNZ, Auckland, New Zealand) which measured bar velocity (m.s^{-1}) and eccentric phase duration (s). Live bar position-time data and a target graphic were displayed on a large digital screen in front of participants to aid in the attainment of the prescribed movement speed. During familiarization participants completed warm up sets at 50% (5 repetitions), 80% (3 repetitions) and 110% (1 repetition) of their self-reported concentric back squat 1RM, followed by increases of 5% until there was a clear failure to control the descent at the allocated velocity [43, 80]. Individual variation in descent velocity was also determined as the mean standard deviation in bar velocity across each third of the descending range of motion (i.e. 180-150°, 150-120°, and 120-90°) of the final three successful attempts of the familiarization session. During the experimental testing session participants completed warm up sets at 50% (5 repetitions), 70%, 85%, and 95% (1 repetition each) of the approximate eccentric 1RM determined during familiarization. Attempts were made at increases of 5% thereafter, separated by 3-5 minutes of passive rest. Failure to control the load was expected to occur at a knee joint angle of approximately 100° [276]. Therefore, two criteria were used to ascertain isoinertial eccentric failure during the experimental trial; 1) the clear failure to control the descent at the allocated velocity; and 2) an increase in bar velocity during the bottom third of the range of motion (i.e. 120-90°) that was two standard deviations above the individual variation in bar velocity determined during familiarization. This method provided an additional objective criteria for eccentric failure compared with previous investigations which exclusively utilized a metronome and subjective evaluation [43, 80]. Isoinertial eccentric force (N·kg^{-1}) was determined as the mean force produced during the final successful repetition. Force was calculated via

differentiation of known mass and measured bar velocity. We have previously investigated the validity and reliability of this protocol within our laboratory (Chapter 4). The differentiation of position data was demonstrated to be a valid alternative to the direct measurement of ground reaction forces by a force platform ($r > 0.99$, mean bias: 0.8%), and the protocol exhibited high inter-day reliability (CV: $< 1\%$).

7.3 Statistical Analysis

Data are presented as mean $\pm$ SD and ES (± 90 % CL) statistics were used to determine the magnitude of differences between the two groups [280]. The smallest worthwhile difference was calculated as 0.2 multiplied by the between subject SD based on Cohen's ES principle [279]. Threshold values for ES was set as: ≤ 0.2 trivial, > 0.2 small, > 0.6 moderate, > 1.2 large, > 2.0 very large, and > 4.0 extremely large [280]. Probabilities were calculated to establish whether the true differences were lower, similar or higher than the smallest worthwhile change or difference. Quantitative chances of higher or lower differences were qualitatively evaluated as follows: < 1 % almost certainly not, 1-5 % very unlikely, 5-25 % unlikely, 25-75 % possible, 75-95 % likely, 95-99 % very likely, >99 % almost certain. If the chance of higher or lower differences was $> 5\%$ the true difference was deemed to be unclear [280]. Pearson Product-Moment Correlations were used to determine the correlation coefficient (r) between selected variables. The magnitude of the correlation between variables was determined via the following criteria: ≤ 0.10 trivial, > 0.11-0.29 small, > 0.30-0.49 moderate, > 0.50-0.69 large, > 0.70-0.89 very large, and > 0.90-1.0 almost perfect [280].

7.4 Results

7.4.1 Differences between team sport athletes and highly trained sprinters

There was a very likely large difference in maximum velocity (+0.86 m·s⁻¹, ES $\pm 90\%$ CL: 1.54 ± 0.85) between team sport athletes and trained sprinters (Table 7.2), corresponding with very likely large differences in contact time (-0.010s, ES: -1.39

±0.80) and vertical stiffness (+0.15 kN·m·kg^{-1}, ES: 1.74 ±0.96). Smaller differences were seen for flight time (+0.005s, ES: 0.35 ±0.54) and step length (+0.12 m, ES: 1.00 ±0.92). No clear differences were observed between groups for step rate or leg stiffness. Trained sprinters exhibited a moderately higher RSI (+0.26, ES: 0.71 ±0.74) which was underpinned by a possibly briefer contact time (-0.009s, ES: -0.38 ±0.58), moderately higher braking peak force (+11 N·kg^{-1}, ES: 0.80 ±0.71), braking mean force (+4 N·kg^{-1}, ES: 0.78 ±0.91) and propulsive mean force (+2 N·kg^{-1}, ES: 0.69 ±0.68). A possible small difference was observed between groups for isoinertial eccentric force (+2 N·kg^{-1}, ES: 0.38 ±0.56).

Table 7.2. Performance data for team sport athletes ($n = 13$) and highly trained sprinters ($n = 11$).

	Team Sport Mean ± SD	Trained Sprint Mean ± SD	ES (90% CI)	Qualitative Inference
Maximum Velocity Sprint Variables				
Maximum Velocity (m·s⁻¹)	8.60 ± 0.52	9.45 ± 0.76	1.54 (0.69; 2.39)	Very Likely Large Difference
Contact Time (s)	0.111 ± 0.007	0.101 ± 0.009	-1.39 (-2.20; -0.59)	Very Likely Large Difference
Flight Time (s)	0.122 ± 0.014	0.127 ± 0.009	0.35 (-0.19; 0.88)	Possible Small Difference
Step Rate (Hz)	4.31 ± 0.26	4.40 ± 0.27	0.34 (-0.33; 1.02)	Unclear
Step Length (m)	1.96 ± 0.11	2.08 ± 0.19	1.00 (0.08; 1.92)	Likely Moderate Difference
Vertical Stiffness (kN·m·kg⁻¹)	0.59 ± 0.08	0.74 ± 0.14	1.74 (0.78; 2.69)	Very Likely Large Difference
Leg Stiffness (kN·m·kg⁻¹)	0.36 ± 0.09	0.39 ± 0.09	0.25 (-0.41; 0.91)	Unclear
0.50m Drop Jump Variables				
Reactive Strength Index	2.71 ± 0.35	2.98 ± 0.42	0.73 (-0.01; 1.47)	Likely Moderate Difference
DJ Contact Time (s)	0.181 ± 0.016	0.171 ± 0.023	-0.38 (-1.96; 0.20)	Possible Small Difference
DJ Flight Time (s)	0.487 ± 0.056	0.503 ± 0.040	0.32 (-0.35; 0.99)	Unclear
DJ Leg Stiffness (kN·m·kg⁻¹)	0.40 ± 0.07	0.44 ± 0.11	0.46 (-0.24; 1.16)	Unclear
DJ Braking Peak Force (N·kg⁻¹)	79 ± 13	90 ± 15	0.80 (0.09; 1.50)	Likely Moderate Difference
DJ Braking Mean Force (N·kg⁻¹)	48 ± 5	52 ± 7	0.78 (-0.13; 1.69)	Likely Moderate Difference
DJ Propulsive Peak Force (N·kg⁻¹)	55 ± 5	58 ± 9	0.47 (-0.55; 1.55)	Unclear
DJ Propulsive Mean Force (N·kg⁻¹)	32 ± 3	34 ± 3	0.69 (0.01; 1.38)	Likely Moderate Difference
Lower Limb Isoinertial Eccentric Strength				
Isoinertial Eccentric Force (N·kg⁻¹)	23 ± 4	24 ± 3 *	0.38 (-0.18; 0.94)	Possible Small Difference

Abbreviations: CI: confidence interval; ES: effect size; Hz: Hertz; kN·m·kg⁻¹: kilonewtons per metre per kilogram; m: metre; m·s⁻¹: metres per second; N·kg⁻¹: Newtons per kilogram; s: seconds; SD: standard deviation; *$n = 10$.

7.4.2 Association between maximum velocity sprinting performance, stiffness regulation, reactive and eccentric strength

Large to very large correlations were observed between maximum velocity and underlying kinematic variables across team sport athletes and highly trained sprinters (Table 7.3). Vertical stiffness was almost perfectly correlated with contact time ($r = -0.99$) and subsequently exhibited a large correlation with step rate ($r = 0.56$). RSI demonstrated large to very large associations with maximum velocity ($r = 0.72$), step rate ($r = 0.79$), contact time ($r = -0.67$), step length ($r = 0.55$) and vertical stiffness ($r = 0.67$). Isoinertial eccentric force was largely correlated with maximum velocity ($r = 0.56$), step rate ($r = 0.56$) and RSI ($r = 0.60$). Large and moderate correlations were observed between vertical stiffness at maximum velocity, DJ mean braking force and isoinertial eccentric force, respectively (Figure 7.1). Furthermore, there was a large association between DJ leg stiffness and vertical stiffness at maximum velocity (Figure 7.2).

Table 7.3. Correlation matrix between maximum velocity kinematic variables, reactive strength and eccentric strength for team sport athletes and highly trained sprinters ($n = 24$). Correlations presented as Pearson r (90% confidence intervals).

	Maximum Velocity (m·s⁻¹)	Contact Time (s)	Flight Time (s)	Step Rate (Hz)	Step Length (m)	Vertical Stiffness (kN·m·kg⁻¹)	Leg Stiffness (kN·m·kg⁻¹)	Reactive Strength Index
Contact Time (s)	-0.62 [†] (-0.79; -0.34)							
Flight Time (s)	-0.27 (-0.56; 0.08)	-0.12 (-0.50; 0.29)						
Step Rate (Hz)	0.64 [†] (0.38; 0.81)	-0.59 [†] (-0.80; -0.24)	-0.73 [††] (-0.86; -0.51)					
Step Length (m)	0.72 [††] (0.50; 0.85)	-0.24 (-0.59; 0.18)	-0.25 (-0.55; 0.10)	0.37 (-0.04; 0.67)				
Vertical Stiffness (kN·m·kg⁻¹)	0.62 [†] (0.35; 0.80)	-0.99 [Ω] (-0.99; -0.97)	0.15 (-0.20; 0.47)	0.56 [†] (0.20; 0.78)	0.28 (-0.07; 0.57)			
Leg Stiffness (kN·m·kg⁻¹)	-0.32 (-0.60; 0.03)	-0.50 [†] (-0.75; -0.12)	0.66 [†] (0.41; 0.82)	-0.19 (-0.55; 0.22)	-0.40 (-0.66; -0.07)	0.50 [†] (0.18; 0.72)		
Reactive Strength Index	0.72 [††] (0.51; 0.86)	-0.67 [†] (-0.82; -0.42)	-0.39 (-0.65; -0.06)	0.79 [††] (0.61; 0.89)	0.55 [†] (0.26; 0.75)	0.67 [†] (0.42; 0.82)	-0.07 (-0.41; 0.28)	
Isoinertial Eccentric Force (N·kg⁻¹)	0.56 [†] (0.26; 0.76)	-0.42 (-0.67; -0.08)	-0.30 (-0.59; 0.06)	0.56 [†] (0.26; 0.76)	0.18 (-0.19; 0.50)	0.41 (0.07; 0.67)	-0.17 (-0.50; 0.19)	0.60 [†] (0.31; 0.79)

Abbreviations: Hz: hertz; kN·m·kg⁻¹: kilonewtons per metre per kilogram; m: metre; m·s⁻¹: metres per second; N·kg⁻¹: newtons per kilogram; s: seconds; [†]: Large Correlation; [††]: Very Large Correlation; [Ω]: Almost Perfect Correlation.
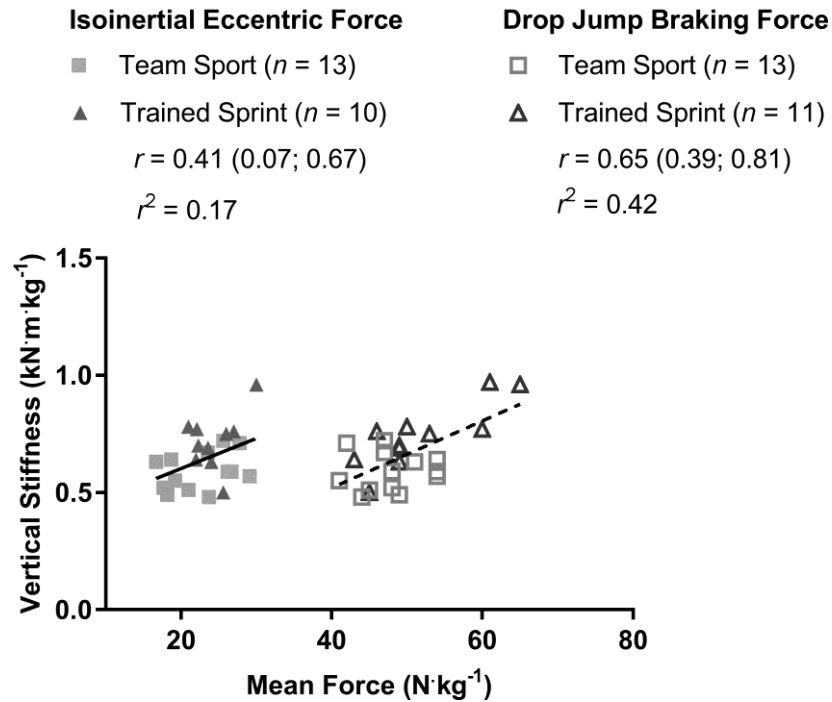
Figure 7.1. Pearson correlation (*r*) between vertical stiffness at maximum velocity, mean isoinertial eccentric force (*n* = 23), and drop jump braking force (*n* = 24) for team sport athletes and highly trained sprinters.
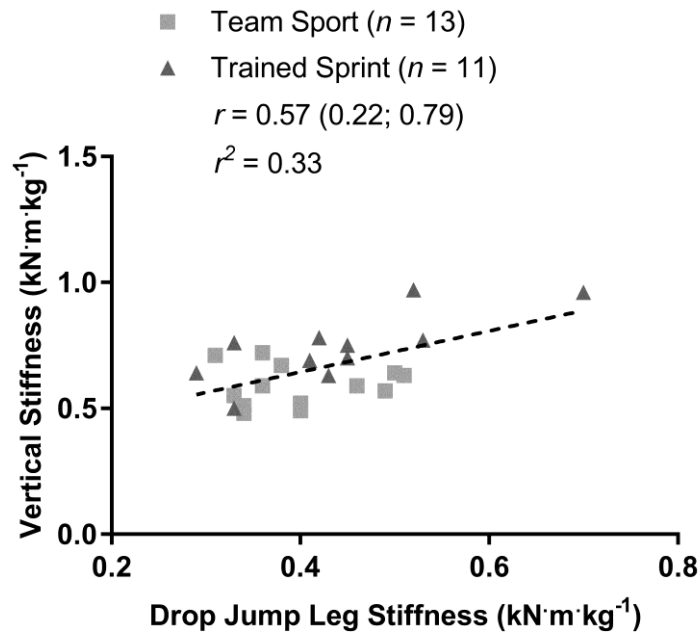
Figure 7.2. Pearson correlation (*r*) between vertical stiffness at maximum velocity and drop jump leg stiffness (*n* = 24) for team sport athletes and highly trained sprinters.

7.5 Discussion

Faster sprinters attain higher maximum velocities via the application of larger vertical ground reaction forces. It is proposed that lower limb stiffness plays a prominent role in the ability to rapidly absorb, and subsequently return, large vertical forces. This is the first study to investigate the association between reactive and eccentric strength qualities and stiffness regulation during maximum velocity sprinting in team sport athletes and highly trained sprinters. Our hypothesis was confirmed and trained sprinters exhibited superior reactive and eccentric strength qualities, stiffness regulation and a higher maximum velocity. The higher maximum velocities attained by trained sprinters were achieved with briefer contact times and longer step lengths. A higher vertical stiffness indicates that trained sprinters exhibited the capacity to rapidly absorb and return larger vertical ground reaction forces versus team sport athletes. This capacity was strongly associated with measures of reactive strength (i.e. RSI, braking force and leg stiffness), while weaker associations were observed with isoinertial eccentric strength. Differences between groups and subsequent associations with performance therefore became progressively smaller with decreasing assessment specificity. However, a large relationship was observed between reactive and eccentric strength qualities. Although we did observe high associations between strength assessments and sprinting performance, the generally limited shared variance between variables (i.e. an r^2 of 60% or less) indicates that neuromuscular and technical abilities not measured in this study likely also contribute to stiffness regulation and maximum velocity sprinting performance.

7.5.1 Kinematic determinants of maximum velocity speed

Step rate and step length were both strongly associated with maximum velocity sprinting speed. Indeed, this finding was expected as these two variables should collectively account for sprinting velocity [326]. While trained sprinters attained longer step lengths than team sport athletes, there were no clear differences in step rate. The longer flight time exhibited by trained sprinters attenuated any differences in step rate, as a briefer contact time was a distinguishing feature of this group. This has previously been observed in well trained sprinters [328]. This finding closely aligns with a

previous report where a briefer ground contact time at a faster maximum velocity was attained via the production of higher vertical ground reaction forces in trained sprinters, with no differences in aerial (i.e. flight) time [20]. Therefore, we may conclude that highly trained sprinters in the present study attained a faster maximum velocity via the application of higher vertical ground reaction forces in a briefer ground contact time [18, 20, 21]. The very strong relationship between contact time and vertical stiffness was expected, and it is likely that lower limb stiffness regulation plays a critical role in attaining a rapid ground contact [24]. It should be acknowledged that there were no clear differences in modelled leg stiffness at maximum velocity between groups, while leg stiffness was only moderately associated with vertical stiffness and contact time. It has previously been shown that vertical stiffness is closely associated with sprinting speed, whereas leg stiffness is not [316, 333]. Furthermore, in a cohort of trained sprinters it was demonstrated that vertical stiffness and ankle stiffness increased in conjunction with improvements in maximum sprinting velocity (i.e. from 9.15 to 9.67 m·s^{-1}) while leg stiffness did not change [330]. These findings may be partly explained by the limitations of a leg stiffness model which attempts to account for the angle swept by the leg on ground contact. It is possible that the model overestimates the distance between the centre of mass and the force vectors point of origin at maximum velocity, and therefore underestimates stiffness [329].

7.5.2 Reactive strength, eccentric strength and stiffness regulation at maximum velocity

The DJ is commonly used as an assessment of lower limb reactive strength specific to maximum velocity sprint performance, and the RSI is considered to reflect an athletes' ability to rapidly absorb and return vertical ground reaction forces [16, 334]. The higher RSI in trained sprinters versus team sport athletes was primarily attained by a briefer and more forceful ground contact phase which allowed them to attain a given flight time. A short and forceful ground contact phase characteristic of a reactively strong individual is postulated to be attained by a stronger quasi-isometric muscle action (i.e. of the knee extensors and ankle plantar flexors), a superior utilization of elastic structures, and a higher RFD within the SSC [11, 334]. This capability is proposed to have a direct influence on stiffness regulation at maximum velocity. Specifically, an enhanced ability to strike the ground with a stiffer leg spring and attain larger braking

forces during a DJ was closely associated with vertical stiffness at maximum velocity. In contrast, eccentric strength may aid stiffness regulation at maximum velocity via a positive effect on reactive strength. Although there were only small differences in isoinertial eccentric strength between team sport athletes and trained sprinters, eccentric strength was closely associated with reactive strength across both groups. An eccentrically stronger muscle is likely to be a stiffer muscle which yields less upon ground contact [320]. While agonists generally act quasi-isometrically during a DJ, some fascicle lengthening still occurs [11]. Therefore, a more forceful eccentric action within the braking phase may potentiate subsequent quasi-isometric and concentric force production within the propulsive phase via residual force enhancement [25], stretch reflex potentiation and Golgi-tendon organ disinhibition [16]. It should be acknowledged that the isoinertial eccentric strength of the ankle plantar flexors was not measured. While the knee extensors are proposed to be the primary regulator of lower limb stiffness during sprinting [329], the ankle plantar flexors must tolerate large joint moments during both drop jumping and sprinting tasks [24, 293]. Therefore, not accounting for eccentric plantar flexor strength may have partly attenuated the observed differences between groups.

It is also possible that a certain threshold of eccentric strength is necessary, beyond which improvements in reactive strength are attained by changes in neuromuscular activation. Indeed, it has previously been demonstrated in trained sprinters that higher levels of reactive strength are attained by the development of a more effective DJ motor strategy (i.e. co-ordination and activation pattern preceding and during ground contact) independent of changes in maximal strength or RFD capabilities of the ankle plantar flexors and knee extensors [304]. This raises the question as to whether we should consider reactive strength as a strength quality *per se*; rather it could be considered a specific motor skill (e.g. "reactive ability") that is influenced by, but not entirely dependent upon, maximum strength (i.e. eccentric, isometric or concentric). Therefore, the role of motor skill in attaining a high level of reactive strength cannot be discounted, and it is proposed that stiffness regulation at maximum velocity may also be largely governed by motor ability versus maximum strength capabilities. It is possible that the strong associations observed were a product of a developed and partly shared coordinative structure (i.e. stiffness regulation) expressing under similar task constraints (i.e. a rapid and forceful ground contact phase) [18]. Therefore, the neuromuscular

regulation (i.e. "skill") of stiffness under task-specific conditions may be equivalently as, if not more, important rather than strength qualities *per se*.

7.6 Conclusion

Trained sprinters exhibited an enhanced regulation of lower limb stiffness at a higher maximum sprinting velocity than team sport athletes. Superior reactive strength, attained by the application of more force in less time, appears to contribute to the ability to regulate stiffness at maximum velocity. Isoinertial eccentric strength on the other hand may have less of a direct impact on maximum velocity sprinting performance, although sufficient eccentric strength may be necessary to exhibit high levels of reactive strength. The inclusion of reactive and eccentric strength training may therefore aid leg spring stiffness regulation at maximum velocity, and subsequently, the attainment of a faster maximum sprinting velocity in team sport athletes and highly trained sprinters alike. However, it is proposed that stiffness regulation is a task-specific neuromuscular skill, and therefore strength training should remain an adjunct to specific maximum velocity sprint training.

Effects of Accentuated Eccentric Loading on Muscle Properties, Strength, Power and Speed in Resistance-Trained Rugby Players

8.0 Lead Summary

In the previous chapters, methods of assessing isoinertial eccentric strength (Chapter 4) and eccentric muscle function under high force fast SSC conditions (Chapter 5) were investigated. Subsequently, these methods were used to infer the role of eccentric muscle function in reactive strength (Chapter 6) and maximum velocity sprinting ability (Chapter 7) in highly trained sprinters and team sport athletes. This final study investigated the effects of eccentrically emphasised training on strength, power, speed and muscle properties in resistance trained Rugby players. Specifically, assessments of reactive strength and maximum velocity sprint performance were included to address the role of eccentric training in improving fast SSC function and stiffness regulation during a high force locomotive task. It is thought that the eccentric contraction speed (i.e. slow versus fast) implemented within training may influence the nature and magnitude of adaptation, while few studies investigating eccentric training methods have recruited well trained athletes undertaking a broader physical preparation program. Therefore, the purpose was to compare the effects of slow and fast tempo traditional (TRAD) resistance training with a program incorporating accentuated eccentric loading (AEL) on muscle properties, strength, power and speed in resistance trained Rugby players. Fourteen subjects (Mean $\pm$ SD: 19 $\pm$ 1 y, 1.82 $\pm$ 0.05 m, 97.0 $\pm$ 11.6 kg, relative back squat 1RM: 1.71 $\pm$ 0.24 kg·BM^{-1}) completed either TRAD ($n = 7$) or AEL ($n = 7$) strength and power protocols. Two 4-week training phases (i.e. slow and fast tempo) were completed. Back squat 1RM, inertial load peak power, optimal cadence, DJ RSI, 40m speed and maximum velocity were determined. Vastus lateralis (VL) muscle architectural variables were assessed via ultrasound. Slow AEL elicited superior improvements in back squat 1RM (+0.12 kg·BM^{-1}; ES: 0.48 $\pm$0.34), 40m time (-0.07 s; ES: -0.28 $\pm$0.27), maximum velocity (+0.2 m·s^{-1}; ES: 0.52 $\pm$0.34) and vertical stiffness at maximum velocity (+0.05 kN·m·kg^{-1} ES: 1.12 $\pm$0.72) versus slow TRAD training. There was a likely greater increase in optimal cadence with slow TRAD (+3.6 RPM; ES: 0.52 $\pm$0.64) versus slow AEL. Fast AEL elicited a small increase in RSI, but impaired speed. There was a likely greater increase in peak power with fast TRAD (+0.72 W·kg^{-1}; ES: 0.40 $\pm$0.39) versus fast AEL. A small increase in VL pennation angle was exhibited following fast TRAD. The short-term incorporation of slow AEL was superior to TRAD in improving strength, maximum velocity sprinting speed and

vertical stiffness in Rugby players undertaking a concurrent preparatory program. The second 4-week phase of fast AEL may have exceeded recovery capabilities and an impairment in speed was observed. Therefore, it appears that a short period of eccentrically emphasized training can rapidly improve lower body strength, maximum velocity sprinting speed and stiffness regulation in resistance trained team sport athletes. However, prolonged periods of eccentric training may be inappropriate in a team sport context in the absence of a sufficient recovery duration preceding competition.

8.1 Introduction

Resistance training is an integral component of physical preparation for team sport athletes [189]. Physical characteristics improved by resistance training such as strength, power and speed have been found to be associated with successful match outcomes [335] and performance levels [336, 337] in Rugby Union athletes. TRAD resistance training strategies (i.e. utilizing the same isoinertial load during both eccentric and concentric phases of a given exercise) are therefore widely used in Rugby Union physical preparation programs [338]. However, as greater forces may be produced during eccentric versus concentric contractions [43, 116], the eccentric phase may be insufficiently loaded during TRAD training programs. Indeed, compelling evidence indicates that AEL of traditional resistance training exercises can induce greater enhancements of strength, power and speed versus TRAD resistance training alone [58, 67]. AEL can be defined as the inclusion of additional eccentric load that exceeds the concentric load for a given exercise, in an effort to account for the differences between eccentric and concentric strength levels. AEL resistance training which accounts for eccentric strength has been demonstrated to elicit a novel adaptive signal within the neuromuscular system [339]. Subsequently, superior adaptations in strength, power and speed have been reported following chronic training with eccentric overload [58, 63, 64]. The performance improvements observed with AEL are proposed to result from increased volitional agonist activation, increased muscle fascicle length, muscle hypertrophy, a shift towards a faster muscle phenotype (e.g. preferential fast twitch fibre hypertrophy and a possible increase in Type IIx fibre composition) and enhancements in SSC function [2, 58, 75]. In addition, there is evidence to suggest that the implementation of faster eccentric contraction velocities or tempos in training may elicit greater improvements in fast muscle phenotypic properties, strength, power, reactive strength and sprinting performance than slower eccentric speeds [63, 75-77]. These findings may be underpinned by a relatively flat eccentric force-velocity relationship allowing the production of high muscle forces at high contraction velocities [41].

Rugby Union athletes are required to develop several conflicting adaptations simultaneously (e.g. maximal strength and aerobic power) [338]. While simultaneous improvements can be made across divergent components of fitness, concurrent training

possibly attenuates the magnitude of adaptation [340]. Therefore, the inclusion of AEL at varying tempos may be a particularly useful method of further stimulating the neuromuscular system within a concurrent training program for the Rugby athlete. Indeed, previous investigations have identified isoinertial [64] and flywheel [227, 341] eccentric training protocols to be effective in enhancing measures of strength, power and speed performance in highly trained team sport athletes with a concurrent aerobic training component. However, to date there have been no investigations comparing isoinertial AEL training (i.e. utilizing both eccentric and concentric phases of the movement) with a control group completing an ecologically valid TRAD training program in resistance trained Rugby players. In the absence of a control group completing a TRAD training protocol, it remains unclear whether the previously reported findings were a result of AEL *per se*, or simply the inclusion of a resistance training program. Furthermore, no studies have compared the effects of slow and fast tempo AEL protocols with equivalent TRAD protocols.

Therefore, the purpose of this investigation was to elucidate the effects of an 8-week periodized AEL training intervention compared with TRAD resistance training (i.e. a control group completing an ecologically valid resistance training program) on muscle properties, strength, power and speed in resistance-trained academy Rugby players integrated within a concurrent training program (e.g. conditioning, skill and competition components). It was postulated that AEL would elicit superior enhancements in strength, power and speed alongside an increase in muscle thickness and fascicle length compared with TRAD. Furthermore, it was proposed that due to the principle of specificity, slow AEL would have a larger influence on maximal strength, while fast AEL would have a larger influence on power, reactive strength and sprinting speed.

8.2 Methods

8.2.1 Experimental Approach to the Problem

Resistance-trained academy Rugby Union athletes were recruited to examine the effects of AEL resistance training versus TRAD training on muscle properties, strength, power and speed within an ecologically valid setting. Subjects were within the preparatory

phase of their representative program and had previously completed two four-week TRAD training phases preceding the study period. Subjects were randomly allocated to complete either AEL or TRAD protocols within their resistance training program during the study period. The primary difference between groups was the load used during the eccentric phase of selected strength and power exercises. All other elements of the resistance training program (i.e. exercise selection, sets, reps, tempo and frequency) were matched between groups. In addition, all subjects were recruited from the same provincial Academy program, therefore the weekly schedule and training load was approximately equivalent across all subjects for the duration of the study. Both AEL and TRAD groups completed two four-week training phases (Figure 8.1). The first phase emphasised a slow eccentric phase tempo and the second phase emphasised a fast eccentric phase tempo. Dependent variables including muscle architectural properties, strength, reactive strength, power and speed were measured at three time points during the study period (i.e. pre-testing at baseline, mid-testing following the first training phase, and post-testing following the second training phase). The effects of AEL and TRAD protocols were elucidated via the determination of change scores of dependent variables within and between groups. ES and qualitative inferences were used to determine the magnitude and likelihood of observed effects.
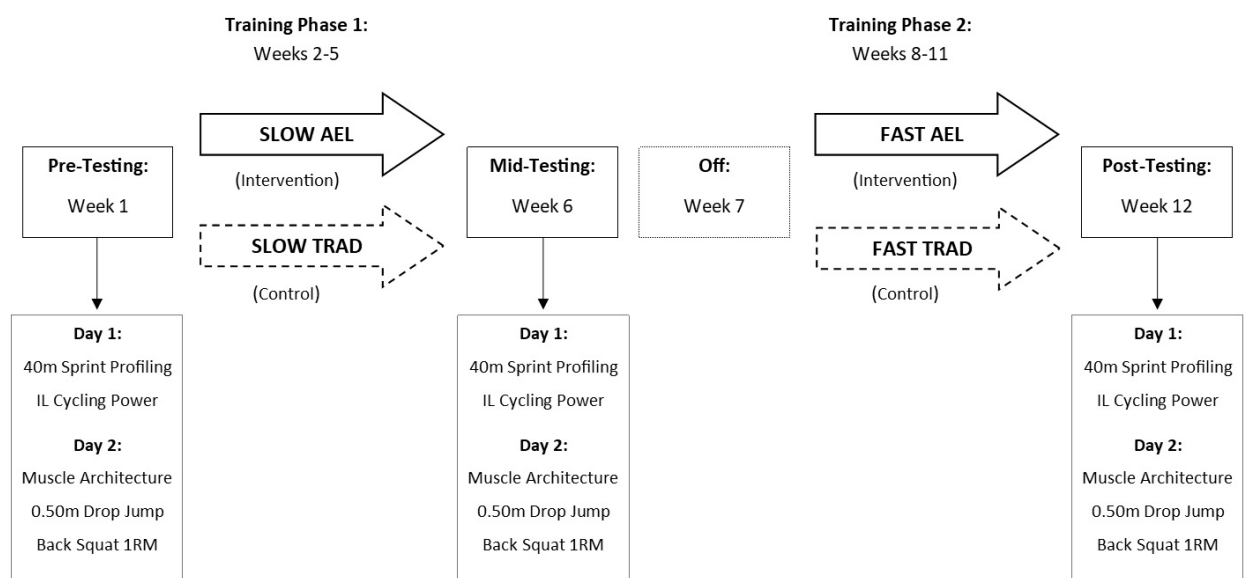
Figure 8.1. Study design.

8.2.2 Subjects

Seventeen male resistance trained academy Rugby players were initially recruited to participate in this study. Following attrition due to contact injury unrelated to the training program ($n = 3$), a final sample of 14 subjects (Mean ± SD: 19 ± 1 years, height: 1.82 ± 0.05 m, weight: 97.0 ± 11.6 kg, relative back squat 1RM: 1.71 ± 0.24 kg·BM^{-1}) were retained for the initial four-week training period. One subject was not included in the second four-week period due to representative selection. All subjects had at least one year of resistance training experience within a supervised program. Subjects were within the preparatory phase of their representative season, although were also participating in a regional club competition (i.e. one ~80-minute Rugby game per week) throughout the duration of the study. Subjects were provided with an overview of all study procedures followed by the completion of informed consent prior to the beginning of the study. All testing protocols complied with AUT ethical guidelines. All testing protocols were approved by the University Ethics Committee.

8.2.3 Resistance training protocols

All subjects completed a combination strength- and power-based gym sessions, conditioning- and skill-based field sessions, and a club Rugby game each week (Table 8.1). This schedule remained consistent throughout the 12-week testing period. Subjects were pair-matched based upon lower body strength and then randomly allocated to either an AEL group ($n = 7$) or a TRAD group ($n = 7$) to be completed within the strength- and power-based gym sessions. Two 4-week training phases separated by 2-weeks were completed. The first 4-week phase emphasised a slower (i.e. 3-second) eccentric tempo, a lower intensity and higher repetitions, while the second 4-week phase emphasised a fast eccentric tempo (i.e. 1-second), a higher intensity and concomitantly lower reps, in the back squat exercise (Table 8.2). The eccentric load for the AEL group was set 18-25% above the TRAD intensity during the strength sessions based on a pilot study which found this to be the typical difference between eccentric and concentric strength levels in the smith machine back squat in resistance trained males. Training load during the strength sessions was matched to within ~10% intensity

relative volume (IRV; intensity [%1RM as a fraction] x sets x reps) between groups
[342]. Therefore, concentric intensity was 4-5% lower in the AEL group.

Table 8.1. Weekly schedule for all subjects ($n = 14$) throughout the 12-week testing
period.

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
AM	Gym Session (Strength)	Gym Session (Power)		Gym Session (Strength)	Rest	Club Game	Rest
PM		Field Session (Conditioning)	Field Session (Skills)	Field Session (Skills)			

Table 8.2. Program prescription for the back squat exercise performed during strength
sessions completed twice weekly.

		Tempo	**Sets x Reps**	**AEL (Intervention)**		**TRAD (Control)**	
				%1RM	**IRV**	**%1RM**	**IRV**
Test	Week 1						
	Week 2	3-0-1*	3x8	92/68**	19	74	18
Slow	Week 3		3x7	95/70	17	76	16
	Week 4		4x6	98/72	20	79	19
	Week 5		2x6	98/72	10	79	10
Test	Week 6						
Off	Week 7						
	Week 8	1-0-1	3x5	106/77	14	81	12
Fast	Week 9		4x4	108/79	15	83	13
	Week 10		5x4	110/81	19	85	17
	Week 11		2x4	110/81	8	85	7
Test	Week 12						

Abbreviations: %1RM: percentage of one repetition maximum; AEL: accentuated
eccentric loading; IRV: intensity relative volume (intensity [%1RM as a fraction] x sets
x reps); Reps: repetitions; TRAD: traditional resistance training. *Tempo denotes
eccentric-transition-concentric phase durations in seconds (s); **Eccentric/Concentric
loading.

The two strength sessions per week (i.e. Monday and Thursday) began with either an AEL or TRAD back squat, while the power session (i.e. Tuesday) began with AEL or TRAD lower body power movements (Table 8.3). Those in the AEL group performed back squats in custom-built smith machine (Goldmine, HPSNZ, Auckland, New Zealand) that provided pneumatic assistance on the lifting (i.e. concentric) portion of the movement to within ± 1 kg of the individualised load. Range of motion was individualised to ensure all subjects were descending to a knee angle of approximately 90° via the use of switches that signified the top and bottom of the movement. These switches were used to initiate the onset and offset of the pneumatic assistance, respectively. Tempo was monitored by a linear position transducer sampling at 250 Hz fixed to the bar (Goldmine, HPSNZ, Auckland, New Zealand). Those in the TRAD group performed a regular back squat with a free barbell in a power rack, subjects were required to descend to a knee angle of approximately 90° at the designated tempo. Power sessions followed a similar periodization scheme in volume (i.e. 3-4 sets of 4-6 reps per exercise) with intensity held constant across each training phase. For the partner AEL kettlebell swing participants were cued to provide maximal eccentric resistance on the negative phase (i.e. "throwing" the kettlebell down) without compromising technique. The eccentric load prescribed for AEL broad jumps was selected to account for differences between eccentric and concentric strength levels without compromising technique. Finally, the load prescribed for AEL DJ's was selected to again account for differences in eccentric and concentric levels, and informed by previous research which identified 20% AEL as the most effective load in eliciting an acute neuromuscular enhancement (i.e. post-activation potentiation) [343], which arguably represents a more potent stimulus for adaptation. All subjects included in the final analysis following attrition completed ≥ 90% of the allocated training program. All training sessions were supervised by two experienced strength and conditioning coaches.

Table 8.3. Exercise selection for subjects completing two 4-week accentuated eccentric loading (AEL) and traditional (TRAD) strength and power programs.

	AEL (Intervention)	TRAD (Control)
Phase 1 – Slow		
Sessions 1 & 3 (Strength)	AEL Smith Machine Back Squat Assistance Lower Body Assistance Upper Body	Back Squat Assistance Lower Body Assistance Upper Body
Session 2 (Power)	AEL Broad Jump (30% BM) Partner AEL Kettlebell Swing Assistance Full Body Power	Broad Jump Kettlebell Swing Assistance Full Body Power
Phase 2 - Fast		
Sessions 1 & 3 (Strength)	AEL Smith Machine Back Squat Assistance Lower Body Assistance Upper Body	Back Squat Assistance Lower Body Assistance Upper Body
Session 2 (Power)	50cm AEL Drop Jump (20% BM) Partner AEL Banded Kettlebell Swing Assistance Full Body Power	50cm Drop Jump Banded Kettlebell Swing Assistance Full Body Power

Abbreviations: BM: body mass; cm: centimeters.

8.2.4 Back squat 1RM

Lower limb muscle strength was determined by the back squat 1RM relative to the subject's body mass in kilograms ($kg \cdot BM^{-1}$). Subjects were required to descend to a knee angle of approximately 90° and touch a plyometric box with posterior thighs. Following four warm up sets of 30% (8-10 repetitions), 50% (4-6 repetitions), 70% (2-4 repetitions) and 90% (one repetition) of the estimated 1RM (i.e. based on recent testing loads) the load was increased until the resistance could not be overcome, with the intention of attaining the 1RM within 3-4 attempts [344]. Subjects were instructed to rest passively for 3-5 minutes between maximum attempts. The back squat 1RM has previously been demonstrated to exhibit high (CV: < 5%) absolute inter-day reliability in a cohort of subjects exhibiting similar strength levels to those recruited in the present study [345].

8.2.5 Inertial load cycling power

A custom built inertial load (IL) cycle ergometer (Goldmine, HPSNZ, Auckland, New Zealand) was used to assess concentric muscle power of the lower limb [346]. The IL assessment involves the determination of torque delivered to an ergometer flywheel across a range of pedalling rates [347]. The product of flywheel inertia, angular velocity and angular acceleration with no frictional resistance applied to the flywheel is used to calculate power [347]. Following a warm up subjects completed three trials separated by two minutes. Subjects started from a stationary position and accelerated maximally for 4-6 seconds (i.e. 6.5 revolutions) on a verbal command with standardised encouragement [346]. Seat and handle heights were self-selected by the subject and remained the same across all testing periods. Instantaneous power and torque data were sampled continuously (i.e. every 3° of crank rotation) and collected via a custom LabVIEW program (National Instruments corp., Austin, TX, USA) on a personal laptop, and exported to a custom spreadsheet where the parabolic power-velocity and linear torque-velocity relationships were calculated [346]. Peak power ($W \cdot kg^{-1}$) and the cadence at which peak power occurred (RPM) were determined. Similar to a previous report [347], this protocol exhibited acceptable inter-day reliability within pilot testing (CV: < 5%). It has been shown in active subjects without cycling experience that two familiarization sessions are necessary for the reliable determination of peak power [347], however the sample recruited in the present study regularly completed maximum cycling power assessments in training and therefore only one familiarization session was completed.

8.2.6 Reactive Strength

Reactive strength was determined via a DJ assessment completed bilaterally from 0.50m. Based on the findings of chapters 5 and 6, this drop height was chosen as a reliable and optimal drop height to provide a substantial braking load (e.g. a peak braking force of 7-10 x body mass) to be tolerated, without impairing reactive strength. Subjects completed one practice jump followed by three maximal attempts with 30-seconds of recovery between each trial. The three maximal attempts were averaged and used for data analysis. Subjects were instructed to perform the DJs with hands akimbo,

and to step forward from the box avoiding stepping down or jumping up. They were explicitly asked to simultaneously attempt to minimize their ground contact time while maximizing their jump height, but to prioritize a brief ground contact time [293]. Trials in which technique was notably compromised were excluded and repeated. DJs were performed from a plyometric box onto an AMTI force platform sampling at 1000 Hz (AMTI, Watertown, MA, USA). A custom-designed LabView (National Instruments; version 8.2, Austin, TX, USA) program was used to collect and analyse the data. A fourth-order Butterworth low-pass filter with a cut-off frequency of 200 Hz was used to smooth all force-time data. A vertical force threshold of 30 N was used to establish zero force and remove noise of the unweighted platform. The deviation from zero force was used to demarcate the beginning and end of the ground contact phase, and the end of the flight phase. Contact time (s), flight time (s), and RSI (flight time divided by contact time) were determined. Leg spring stiffness ($kN \cdot m \cdot kg^{-1}$) was calculated for each DJ using a method described previously [297]. A pilot investigation (Chapter 5) demonstrated all variables to exhibit acceptable inter-session reliability (CV: 3-9%).

8.2.7 Sprint profiling

Sprint testing was performed in the same lane of the same indoor Mondo track across all testing periods. A standardised ~20 minute warm up including jogging, dynamic stretching and submaximal 40m efforts at 70%, 80% and 90% of self-selected maximal intensity was completed [348]. Following the warm up subjects completed two maximal 40m sprints separated by approximately five minutes. Subjects commenced each sprint from a split stance without a countermovement and instructed to accelerate maximally while avoiding any deceleration prior to the 40m mark. A radar device (Stalker ATS II, Applied Concepts, Dallas, TX, USA) set two metres behind the subject and at the height of the approximate centre of mass (i.e. one metre) was used to capture velocity data at a sampling rate of 46.9 Hz. The radar was operated by a portable laptop using software supplied by the manufacturer (STATS, Applied Concepts, Dallas, TX, USA). Velocity-time data were filtered and clipped at the point of deceleration within the STATS program. A rollout distance of 0.50m was included to enable distance-time data comparable with industry standards (i.e. timing lights). Maximum velocity and time splits at 10m, 20m and 40m (s) were determined. A high-speed video camera recording

at 300 Hz was set adjacent to the track at 35m to capture maximum velocity kinematic variables between 30m and 40m. Footage was transferred onto a personal computer and analysed using video analysis software (Kinovea 0.8.15). Contact time (s), flight time (s) and step rate (Hz) at maximum velocity were determined from each sprint. Vertical stiffness (K_{vert}) and leg stiffness (K_{leg}) at maximum velocity was modelled using the methods previously described by Morin and colleagues [333]. Previous research has demonstrated radar assessment to be a valid alternative to photoelectric cells [283], and exhibits high (CV: <5%) absolute intra- and inter-day reliability [349].

8.2.8 Muscle architecture

In vivo muscle architecture was measured using two-dimensional (2D) B-mode ultrasonography using an ultrasound transducer (45mm linear array, 10 MHz; GE Healthcare, Vivid S5, U.S.A). Subjects lay supine on an adjustable bench with their right knee fixed at 45° with muscles relaxed. This joint angle was chosen to minimise fascicle curvature [350]. The location of the scan was taken at 50% of the femur length and the VL muscle was scanned [351]. Water soluble transducer gel was applied to the probe head between the skin-probe interface to aid acoustic contact and allow for minimal compression of the muscle [351]. Scans were performed with the transducer aligned parallel to the muscle fascicles and perpendicular to the skin [194]. Images were stored and transferred to a personal computer to be analysed in digitizing software (ImageJ, 1.51j8, National Institutes of Health, USA). VL muscle thickness (cm) was taken as the perpendicular distance between the deep and superficial aponeurosis, and fascicle angle (θ) was defined as the angle of the VL muscle fascicles relative to the deep aponeurosis of insertion [352]. As the fascicles often extended beyond the recorded image, fascicle length (cm) across the deep and superficial aponeurosis was estimated by the following equation:

$$\text{Fascicle Length} = MT \times (\sin\theta)^{-1}$$

Where MT refers to VL muscle thickness and θ refers to VL fascicle angle [353]. The average of three scans was taken for each variable. A pilot study found this protocol to exhibit acceptable inter-day reliability for all three variables (CV: <5%).

8.3 Statistical Analysis

Data are presented as mean ± SD. ES (±90 % CL) statistics were then used to determine the magnitude of change within and between the two groups [280]. The smallest worthwhile change or difference was calculated as 0.2 multiplied by the between subject SD based on Cohen's ES principle [279]. Threshold values for ES was set as: ≤ 0.2 trivial, > 0.2 small, > 0.6 moderate, > 1.2 large, > 2.0 very large, and > 4.0 extremely large. Probabilities were calculated to establish whether the true differences were lower, similar or higher than the smallest worthwhile change or difference. Quantitative chances of higher or lower differences were qualitatively evaluated as follows: < 1 % almost certainly not, 1-5 % very unlikely, 5-25 % unlikely, 25-75 % possible, 75-95 % likely, 95-99 % very likely, >99 % almost certain. If the chance of higher or lower differences was > 5%, the true difference was deemed to be unclear [280].

8.4 Results

8.4.1 Pre-testing differences

Following attrition, several small to moderate differences in performance variables were observed between TRAD and AEL groups during pre-testing (i.e. baseline). Inertial load peak power (ES [±90 % CL]: 0.87 ±0.89) and optimal cadence (ES: 1.11 ±0.84) were moderately higher in AEL versus TRAD, respectively. DJ RSI (ES: 0.99 ±0.85) and flight time (ES: 0.85 ±0.90) were both moderately higher in the AEL group versus the TRAD group. Subjects in the AEL group exhibited moderately faster 10m (ES: -1.05 ±0.87), 20m (ES: -1.01 ±0.87) and 40m (ES: -1.08 ±0.84) times versus the TRAD group in conjunction with a moderate difference in maximum velocity (ES: 1.13 ±0.81).

8.4.2 The effects of slow AEL and TRAD training protocols

Upon completion of the first 4-week training phase, a small improvement was found in back squat strength for those completing slow AEL (Table 8.4), this improvement was

likely superior (+0.12 kg·BM^{-1}; ES: 0.48 ±0.34) to slow TRAD (Figure 8.2). Slow AEL resulted in small improvements in 20m and 40m times. The improvement in 40m time with slow AEL was possibly superior compared with slow TRAD (-0.07 s; ES: -0.28 ±0.27). Slow AEL training also elicited likely small improvements in maximum velocity, contact time, step rate, leg stiffness. Alternatively, flight time increased with slow TRAD in conjunction with a reduction in step rate (Table 8.5). The reduction in step rate did not appear to impair 40m performance or the attainment of Vmax in the slow TRAD group. Improvements in maximum velocity (+0.2 m·s^{-1}; ES: 0.52 ±0.34), contact time (-0.01 s; ES: -0.45 ±0.33), step rate (+0.2 Hz; ES: -0.83 ±0.56) and vertical stiffness (+0.05 kN·m·kg^{-1}; ES: 0.50 ±0.31) were likely greater with slow AEL versus slow TRAD training. Leg stiffness did not exhibit a clear change with either slow TRAD or AEL protocols.

Table 8.4. Performance data (mean ± SD) for subjects (n = 7) in the intervention group completing an accentuated eccentric loading (AEL) resistance training program. Effect sizes presented as standardised Cohen differences (90 % Confidence Interval).

	Pre-Testing	Mid-Testing (Slow AEL)	Post-Testing † (Fast AEL)	Effect Size (Mid-Pre)	Qualitative Inference	Effect Size (Post-Mid)	Qualitative Inference
Strength & Power Variables							
Relative Back Squat 1RM (kg·BM^{-1})	1.77 ± 0.28	1.86 ± 0.20	1.85 ± 0.18	0.38* (0.04; 0.70)	Likely Higher	-0.04 (-0.07; -0.01)	Unclear
IL Relative Peak Power (W·kg^{-1})	14.4 ± 1.6	15.1 ± 1.6	14.8 ± 0.8	0.44 (-0.22; 1.10)	Unclear	-0.23 (-1.25; 0.78)	Unclear
IL Optimal Cadence (RPM)	132 ± 8	133 ± 7	130 ± 6	0.02 (-0.42; 0.46)	Unclear	-0.34 (-0.98; 0.31)	Unclear
0.50m Drop Jump Variables							
Contact Time (s)	0.22 ± 0.02	0.22 ± 0.02	0.20 ± 0.02	0.01 (-0.71; 0.72)	Unclear	-0.82** (-1.47; -0.17)	Likely Lower
Flight Time (s)	0.49 ± 0.05	0.49 ± 0.04	0.48 ± 0.05	0.01 (-0.28; 0.30)	Unclear	-0.35 (-1.26; 0.55)	Unclear
RSI	2.29 ± 0.32	2.29 ± 0.21	2.41 ± 0.45	-0.03 (-0.53; 0.47)	Unclear	0.37* (-0.19; 0.93)	Possibly Higher
Leg Stiffness (kN·m·kg^{-1})	0.28 ± 0.05	0.28 ± 0.05	0.33 ± 0.06	0.01 (-0.69; 0.72)	Unclear	0.77** (0.14; 1.40)	Likely Higher
40m Sprint Variables							
10m (s)	1.80 ± 0.04	1.79 ± 0.06	1.83 ± 0.05	-0.17 (-0.82; 0.47)	Unclear	0.65** (0.17; 1.13)	Likely Higher
20m (s)	3.08 ± 0.07	3.05 ± 0.09	3.11 ± 0.07	-0.35* (-0.84; 0.14)	Possibly Lower	0.71** (0.25; 1.17)	Very Likely Higher
40m (s)	5.41 ± 0.14	5.36 ± 0.13	5.44 ± 0.12	-0.44* (-0.76; -0.12)	Likely Lower	0.66** (0.39; 0.92)	Almost Certainly Higher
Maximum Velocity Sprint Variables							
Maximum Velocity (m·s^{-1})	8.72 ± 0.24	8.87 ± 0.28	8.72 ± 0.22	0.56* (0.12; 1.01)	Likely Higher	-0.59* (-1.19; 0.01)	Likely Lower
Contact Time (s)	0.12 ± 0.01	0.11 ± 0.01	0.11 ± 0.01	-0.46* (-0.74; -0.19)	Likely Lower	0.32 (-0.68; 1.33)	Unclear
Flight Time (s)	0.11 ± 0.01	0.11 ± 0.01	0.11 ± 0.01	-0.16 (-0.85; 0.53)	Unclear	-0.55 (-1.47; 0.37)	Unclear
Step Rate (Hz)	4.40 ± 0.22	4.48 ± 0.17	4.51 ± 0.14	0.42* (-0.08; 0.93)	Likely Higher	0.21* (-0.18; 0.60)	Possibly Higher
Vertical Stiffness (kN·m·kg^{-1})	0.55 ± 0.08	0.58 ± 0.08	0.56 ± 0.05	0.43* (0.16; 0.69)	Likely Higher	-0.31 (-1.32; 0.70)	Unclear
Leg Stiffness (kN·m·kg^{-1})	0.30 ± 0.05	0.31 ± 0.06	0.31 ± 0.06	0.19 (-0.14; 0.53)	Unclear	-0.08 (-0.76; 0.60)	Unclear

Abbreviations: 1RM: one repetition maximum; Hz; hertz; IL: inertial load bike ergometer; kg·BM^{-1}: kilograms per kilogram of body mass; kN·m·kg^{-1}: kilonewtons per metre per kilogram; s: seconds; RPM: revolutions per minute; RSI: reactive strength index; W·kg^{-1}: watts per kilogram; *: small effect; **: moderate effect; †: *n* = 6.

Table 8.5. Performance data (mean ± SD) for subjects ($n = 7$) in the control group completing a traditional (TRAD) resistance training program. Effect sizes presented as standardised Cohen differences (90 % Confidence Interval).

	Pre-Testing	Mid-Testing (Slow TRAD)	Post-Testing (Fast TRAD)	Effect Size (Mid-Pre)	Qualitative Inference	Effect Size (Post-Mid)	Qualitative Inference
Strength & Power Variables							
Relative Back Squat 1RM (kg·BM⁻¹)	1.65 ± 0.20	1.62 ± 0.20	1.63 ± 0.23	-0.14 (-0.32; 0.04)	Unclear	0.01 (-0.20; 0.22)	Unclear
IL Relative Peak Power (W·kg⁻¹)	12.8 ± 1.8	13.0 ± 1.4	13.8 ± 1.9	0.10 (-0.31; 0.52)	Unclear	0.47* (0.17; 0.78)	Likely Higher
IL Optimal Cadence (RPM)	125 ± 3	129 ± 4	129 ± 7	0.88** (0.06; 1.70)	Likely Higher	0.10 (-0.55; 0.75)	Unclear
0.50m Drop Jump Variables							
Contact Time (s)	0.24 ± 0.04	0.24 ± 0.03	0.24 ± 0.05	0.11 (-0.37; 0.60)	Unclear	0.08 (-0.45; 0.61)	Unclear
Flight Time (s)	0.45 ± 0.04	0.46 ± 0.04	0.46 ± 0.03	0.37* (-0.09; 0.83)	Possibly Higher	-0.25 (-1.18; 0.68)	Unclear
RSI	1.94 ± 0.31	1.96 ± 0.23	1.97 ± 0.56	0.07 (-0.24; 0.38)	Unclear	0.03 (-0.69; 0.74)	Unclear
Leg Stiffness (kN·m·kg⁻¹)	0.26 ± 0.07	0.25 ± 0.07	0.26 ± 0.11	-0.12 (-0.47; 0.23)	Unclear	0.08 (-0.30; 0.46)	Unclear
40m Sprint Variables							
10m (s)	1.90 ± 0.11	1.88 ± 0.12	1.89 ± 0.05	-0.15 (-0.59; 0.29)	Unclear	0.07 (-0.79; 0.92)	Unclear
20m (s)	3.22 ± 0.16	3.20 ± 0.18	3.22 ± 0.09	-0.13 (-0.47; 0.20)	Unclear	0.14 (-0.56; 0.84)	Unclear
40m (s)	5.67 ± 0.26	5.68 ± 0.27	5.72 ± 0.22	0.04 (-0.18; 0.25)	Unclear	0.16 (-0.44; 0.77)	Unclear
Maximum Velocity Sprint Variables							
Maximum Velocity (m·s⁻¹)	8.30 ± 0.37	8.25 ± 0.31	8.14 ± 0.39	-0.14 (-0.37; 0.09)	Unclear	-0.34* (-0.80; 0.12)	Possibly Lower
Contact Time (s)	0.12 ± 0.01	0.12 ± 0.01	0.13 ± 0.01	0.15 (-0.13; 0.43)	Unclear	0.13 (-0.12; 0.37)	Unclear
Flight Time (s)	0.12 ± 0.01	0.12 ± 0.01	0.12 ± 0.02	0.37* (-0.04; 0.78)	Likely Higher	-0.03 (-0.65; 0.58)	Unclear
Step Rate (Hz)	4.19 ± 0.20	4.09 ± 0.22	4.08 ± 0.30	-0.50* (-0.97; -0.04)	Likely Lower	-0.03 (-0.51; 0.46)	Unclear
Vertical Stiffness (kN·m·kg⁻¹)	0.48 ± 0.11	0.47 ± 0.09	0.45 ± 0.10	-0.15 (-0.42; 0.12)	Unclear	-0.21* (-0.59; 0.16)	Possibly Lower
Leg Stiffness (kN·m·kg⁻¹)	0.30 ± 0.06	0.31 ± 0.06	0.30 ± 0.06	0.09 (-0.12; 0.31)	Unclear	-0.20 (-0.70; 0.31)	Unclear

Abbreviations: 1RM: one repetition maximum; Hz; hertz; IL: inertial load bike ergometer; kg·BM⁻¹: kilograms per kilogram of body mass; kN·m·kg⁻¹: kilonewtons per metre per kilogram; s: seconds; RPM: revolutions per minute; RSI: reactive strength index; W·kg⁻¹: watts per kilogram; *: small effect; **: moderate effect.
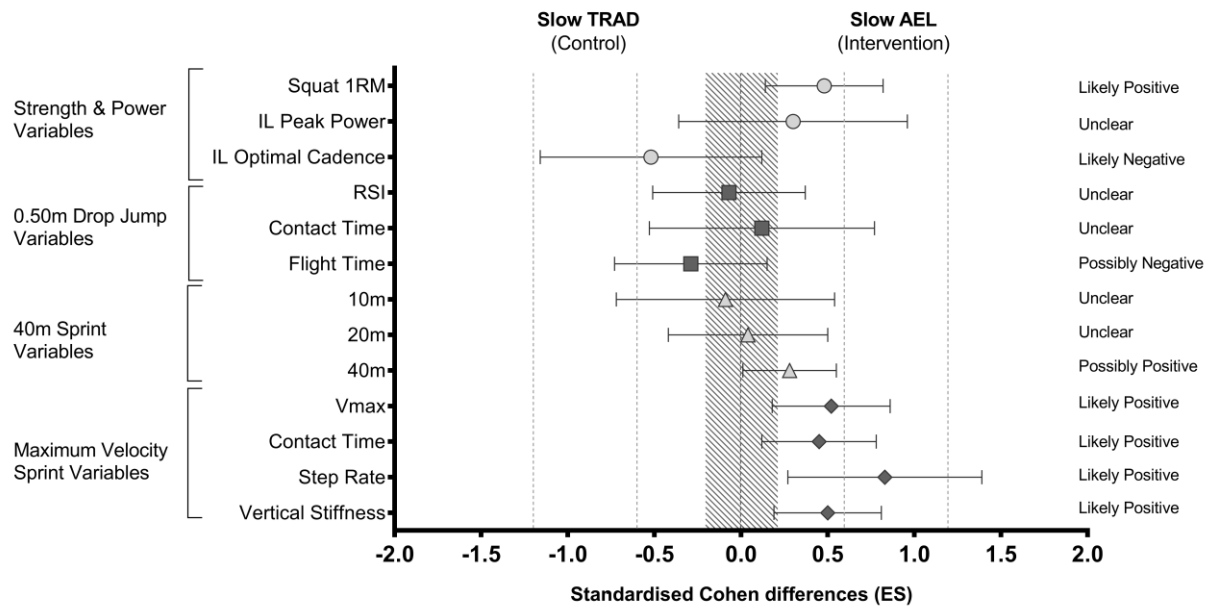
Figure 8.2. The standardised (Cohen) difference for subjects completing slow AEL (*n* = 7) versus subjects completing slow TRAD (*n* = 7). Differences are for the change in selected performance variables. Negative values indicate a larger effect with TRAD and positive values indicate a larger effect with AEL. Qualitative inferences indicate a positive or negative effect of AEL versus TRAD. *Error bars* indicate uncertainty in the true mean changes with 90 % confidence intervals. The *shaded area* represents the smallest worthwhile change. Vmax: maximum velocity.

In contrast to the changes in strength and speed with slow AEL, there was a moderate increase in IL optimal cadence with slow TRAD (Table 8.5), which was likely greater compared with slow AEL (+3.6 RPM; ES: 0.52 ±0.64). There was a possible small increase in DJ flight time with slow TRAD, however this had no effect on the RSI performance measure. Neither slow TRAD nor slow AEL protocols influenced muscle architectural variables (Table 8.6).

Table 8.6. Vastus lateralis muscle architectural data (mean ± SD) for subjects completing slow and fast accentuated eccentric loading (AEL; $n = 7$) and traditional (TRAD; $n = 7$) resistance training programs. Effect sizes presented as standardised Cohen differences (90 % Confidence Interval).

|	AEL (Intervention)					TRAD (Control)				
	Pre-Testing	Mid-Testing (Slow AEL)	Post-Testing (Fast AEL) †	Effect Size (Mid-Pre)	Effect Size (Post-Mid)	Pre-Testing	Mid-Testing (Slow TRAD)	Post-Testing (Fast TRAD)	Effect Size (Mid-Pre)	Effect Size (Post-Mid)
Muscle Thickness (cm)	3.0 ± 0.7	3.1 ± 0.7	3.2 ± 0.7	0.18 (-0.03; 0.39)	0.05 (-0.12; 0.23)	3.2 ± 0.3	3.2 ± 0.3	3.3 ± 0.4	-0.02 (-0.20; 0.16)	0.10 (-0.23; 0.43)
Fascicle Angle (θ)	14.4 ± 2.4	13.9 ± 2.9	14.6 ± 2.5	-0.19 (-0.68; 0.30)	0.25 (-0.61; 1.11)	15.1 ± 1.8	15.1 ± 1.7	15.6 ± 2.0	0.01 (-0.30; 0.33)	0.25* (-0.10; 0.61)
Fascicle Length (cm)	12.2 ± 1.4	13.3 ± 2.1	12.4 ± 1.1	0.61 (-0.21; 1.43)	-0.49 (-1.63; 0.65)	12.6 ± 2.0	12.5 ± 1.5	12.4 ± 2.0	-0.06 (-0.37; 0.25)	-0.07 (-0.52; 0.38)

Abbreviations: cm: centimeters; *: possible small increase; †: $n = 6$.

8.4.3 The effects of fast AEL and TRAD training protocols

Following the second 4-week phase of training, a likely reduction in DJ contact time was observed in the fast AEL group resulting in a possible small increase in RSI and likely moderate increase in leg stiffness (Table 8.4). The reduction in contact time with fast AEL was likely greater (-0.02 s; ES: -0.66 ±0.77) than fast TRAD (Figure 8.3). However, there was no clear difference in RSI. In contrast to the slow phase of training, there were moderate reductions in 10m, 20m and 40m times with fast AEL. Furthermore, there were small reductions in maximum velocity in both fast AEL (Table 8.4) and fast TRAD (Table 8.5) groups. No differences were observed between fast AEL and fast TRAD for any sprint performance variable (Figure 8.3). A small increase in IL peak power was observed with fast TRAD, which was likely greater (+0.72 W·kg^{-1}; ES: 0.40 ±0.39) than fast AEL (Figure 8.3). There was a possible small increase in VL pennation angle with fast TRAD, however no clear difference versus fast AEL was observed (Table 8.6).
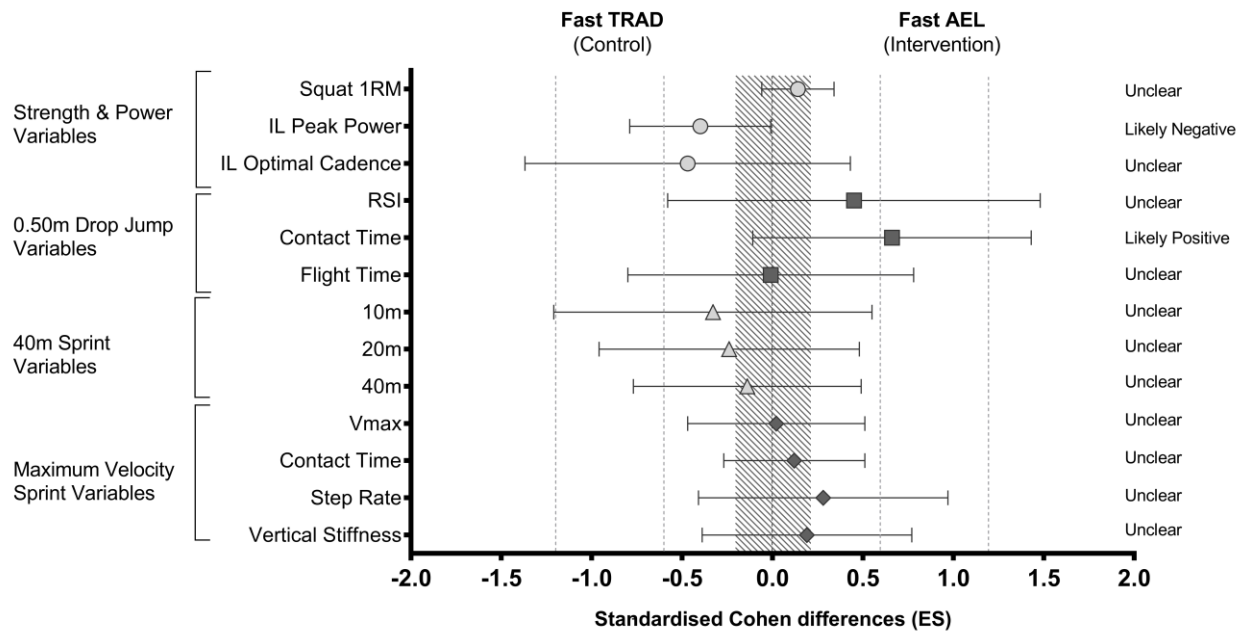
Figure 8.3. The standardised (Cohen) difference for subjects completing fast AEL (*n* = 6) versus subjects completing fast TRAD (*n* = 7). Differences are for the change in selected performance variables. Negative values indicate a larger effect with TRAD and positive values indicate a larger effect with AEL. Qualitative inferences indicate a positive or negative effect of AEL versus TRAD. *Error bars* indicate uncertainty in the true mean changes with 90 % confidence intervals. The *shaded area* represents the smallest worthwhile change. Vmax: maximum velocity.

8.5 Discussion

The present study compared the effects of slow and fast tempo AEL resistance training with TRAD resistance training on muscle properties, strength, power and speed performance. The main finding was that 4-weeks of slow AEL resistance training was superior to slow TRAD resistance training in improving lower body strength and sprinting speed in resistance trained Rugby players when integrated within a concurrent training program. In contrast, besides a possible increase in reactive strength, a second 4-week training phase of fast AEL did not appear to elicit any further improvements in strength or speed, and may have compromised the previously observed enhancements in sprint performance. These results partly support our hypothesis of the superiority of AEL training versus TRAD resistance training in team sport athletes completing a

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concurrent training program. However, the pattern of adaptation differed to what was initially hypothesized. It was also identified that team sport athletes may be less responsive to either fast eccentric stimuli, or susceptible to eccentric-related fatigue and impairments in performance with this periodization approach.

It has been well-established that eccentric training can lead to greater increases in total (i.e. combined eccentric, isometric and concentric) strength than concentric training [67]. The efficacy of eccentric training has been proposed to result from of a combination of neural, morphological and architectural adaptations [58]. The superiority of slow AEL in increasing lower body strength in the present study is arguably underpinned by neural mechanisms as no clear changes in VL muscle thickness, fascicle angle or fascicle length were observed. This assumes that the VL muscle is representative of all primary agonists within the back squat. While program volume (i.e. IRV) was closely matched between AEL and TRAD groups, those completing slow AEL were exposed to absolute loads 18-25% higher than those completing slow TRAD. Exposure to such loads via AEL may have elicited a disinhibition of mechanisms constraining volitional agonist drive and therefore force production [66, 219]. It appears that the TRAD protocol provided an insufficient stimulus to increase strength in 4-weeks in a resistance trained cohort undergoing concurrent aerobic training. Indeed, it has previously been identified the difficulty in increasing strength and power in academy-aged Rugby athletes with a high concurrent training load [354]. This may be explained by the interference phenomenon whereby concurrent aerobic training attenuates the magnitude of adaptation to a given strength program due to divergent phenotypic signals [340, 355]. The upregulation of the molecular pathway responsible for mitochondrial biogenesis with aerobic training is known to inhibit the pathway which signals myofibrillar protein synthesis (i.e. via AMPK downregulating mTOR) therefore blunting hypertrophy, strength and power adaptations [356], particularly in trained individuals [357]. In the present study, concurrent aerobic training possibly attenuated myofibrillar protein synthetic rates in response to both protocols, however the additional neural stimulation with slow AEL elicited a small increase in strength independent of changes in muscle cross-sectional area.

No changes in IL peak power were observed in either group following the slow phase of training. Concentric power is a function of the combined force and velocity properties of muscle [191, 358] which suggests that the increase in strength with slow AEL did not translate into improvements in power. Perhaps in contrast to expectations, those completing slow TRAD however did exhibit an increase in the cadence at which peak power occurred (i.e. IL optimal cadence). A higher optimal cadence is generally thought to reflect a larger proportion of fast twitch muscle fibres comprising the lower limb musculature [359]. However, there is little corroborating evidence with coinciding improvements in speed and power to indicate an increase in fast twitch fibre composition with slow TRAD. Given no change in IL peak power this increase in optimal cadence likely reflects a shift towards a velocity dominant force-velocity profile. Those in the slow TRAD group had a moderately lower initial optimal cadence relative to the AEL group at baseline, and possibly, a more force dominant power profile [358, 360]. The training protocol in the present study may have been a sufficient stimulus to improve velocity-specific neural activation at higher cadences independent of changes in muscle morphological or architectural properties [360, 361], and indeed, concentric power.

Slow AEL induced a superior improvement in 40m sprint performance versus slow TRAD, with no clear differences observed between the groups for the shorter distances. The improvement in 40m sprint performance with slow AEL was accompanied by an increase in maximum velocity and underlying kinematic variables. These findings are of note as recent research has highlighted the importance of maximum velocity capabilities to field sport athletes [325]. It has previously been observed that eccentric training can result in greater improvements in speed than TRAD if additional concentric training (e.g. overspeed jump training) is included [64]. The present findings support this proposition. The ability to apply greater mass specific vertical forces, and possibly, maintain a stiffer leg spring appear to underpin the attainment of a faster maximum velocity [20, 324]; and it has been consistently demonstrated that improvements in back squat (i.e. vertical) strength positively transfer to sprinting speed [362]. The reduced contact time and concomitant increases in step rate and vertical stiffness indicate improvements in mass specific vertical force production and lower limb stiffness following 4-weeks of slow AEL training. It is also thought that the storage and return of energy within elastic structures of the lower limb play an increasingly important role at

higher sprinting speeds up to maximum velocity [6]. As previous research has identified the efficacy of eccentric training protocols in increasing tendon stiffness [69, 263] and upregulating muscle collagen synthesis rates [154], the improvement in maximum velocity with slow AEL may have been partly related to modulated stiffness properties of tendon and fascial elements (i.e. the amplifiers of the MTU) within the lower limb [5]. This in turn could have allowed for an increased storage and return of elastic strain energy [5, 6]. Nonetheless, MTU tissue stiffness was not directly measured in the present study and therefore any contribution remains speculative. Interestingly, while there was an increase in modelled vertical stiffness with slow AEL, no change in modelled leg stiffness was observed. This was not an unexpected finding as vertical stiffness is closely associated with sprinting speed, whereas leg stiffness is not [316, 333]. This may therefore explain the lack of change in leg stiffness in either group across both training phases. There were no changes in DJ RSI for either group following the slow training phase. There was a possible small increase in DJ flight time (i.e. net propulsive impulse) with slow TRAD. The small increase in flight time may have been due to a lower baseline in the TRAD group and the strength and power program might have had a small effect on the capability to rapidly apply a propulsive force, however, it was not sufficient to improve the RSI performance measure. The lack of change in RSI indicates that neither protocol was sufficient to markedly improve the qualities underlying reactive strength. This was not entirely unexpected as neither protocol included specific reactive strength exercises (e.g. DJs) in this phase of training, and this strength quality is considered to be largely influenced by neuromuscular qualities (e.g. muscle pre-activation, reflex excitability and rapid force application) best developed via exposure to the task [302, 304].

The second 4-week phase of training with faster contraction speeds did not induce any further improvements in strength in either group. There was a small increase in IL peak power with fast TRAD which is proposed to reflect the efficacy of the strength and power training [191, 363], or indeed, the incurrence of less fatigue than the fast AEL protocol. A concomitant small increase in VL pennation angle with fast TRAD, which effectively represents a small increase in physiological CSA of the muscle [364], may also have contributed to the observed improvements in IL peak power [191]. Nonetheless, the improvement in peak power was relatively small, which may again be explained by an attenuated training effect due to interference with aerobic stimuli [355].

The apparent detrimental effect of fast AEL on IL peak power versus fast TRAD may have been a result of residual fatigue, chronic eccentric exercise in combination with the concurrent training load possibly suppressed a positive training effect [164, 236, 365]. Indeed, the lack of improvement in strength, moderate impairments in 10m, 20m and 40m sprint performance, and a small impairment in maximum velocity following fast AEL all suggest a fatigue-induced suppression of performance. Previous research has found that improvements in concentric power reached their peak 8-weeks following the cessation of an eccentric training intervention [236], while improvements in concentric force production have been shown to peak after 6-weeks of detraining following eccentric training [366]. A longer recovery period is likely necessary to allow improvements in performance to materialize following an extended (e.g. 8-week) period of chronic eccentric training [58, 236]. Therefore, it is plausible that the post-testing period at the cessation of the second 4-week phase (i.e. after 8-weeks of AEL training) may have been too early to allow the dissipation of fatigue, and to capture the delayed performance effects of the fast AEL training program. This may be especially relevant to Rugby athletes undergoing a concurrent training program whereby residual fatigue is likely to be even greater than in previous reports.

In contrast to the impairments in strength and speed there was an improvement in DJ RSI with fast AEL which was underpinned by a reduction in ground contact time. This finding suggests that reactive strength is either less susceptible to fatigue incurred by chronic eccentric training than other measures, or alternatively, may have exhibited a more substantial improvement had an extended recovery period been available. It is likely that the specific nature of the fast AEL protocol (i.e. overloaded DJs) underpinned these performance responses. It has previously been demonstrated that contact time during a DJ from 0.50m is determined primarily by braking (i.e. eccentric) force production [334]. The inclusion of AEL DJs likely had a marked effect on eccentric force production capabilities which in turn lead to an improvement in contact time during unloaded DJs. It should be acknowledged that the fast TRAD group were also exposed to specific reactive strength training stimuli, however they did not exhibit any clear improvement in RSI. It is possible that volume, intensity, or both, were insufficient to elicit a performance improvement in the absence of eccentric overload.

There were several methodological limitations which may affect the interpretation of these data. We were restricted in the number of subjects available in the training squad and therefore sample size. Following attrition ($n = 3$) due to injury, baseline differences between groups were magnified and subjects within the AEL group were moderately more powerful and faster than the TRAD group. This may therefore have confounded the training responses to several variables. Although it should be noted that it is more difficult to elicit adaptation in individuals with a higher baseline or more training experience [367], thus these differences plausibly attenuated the efficacy of the AEL protocol. We tested one periodization model (i.e. slow followed by fast TRAD and AEL training) and it is not clear whether the performance effects observed were due to tempo per se, or the order of the training blocks. Further research should therefore investigate the effects of fast tempo AEL training without a preceding slow AEL phase. The inclusion of concurrent conditioning training units may be considered a limitation; however, we believe this improved the ecological validity of the study. Finally, it should be acknowledged the limitations of using isoinertial loading to achieve AEL. This method of loading does not guarantee a standardised AEL and movement velocity across a full range of motion, such as could be achieved using an isokinetic modality. This may be especially relevant at faster movement velocities, and could explain the discrepancies between the present findings and previous research using fast isokinetic eccentric training.

These findings are highly relevant to the practitioner seeking to implement eccentric training with trained Rugby or team sport athletes undergoing a broader physical preparation program. The short term (i.e. 4-weeks) incorporation of slow AEL appears to be superior to commonly implemented TRAD resistance training in improving lower limb strength and maximum velocity sprinting speed in Rugby players undertaking a concurrent preparatory program. Aside from a possible improvement in reactive strength, a second 4-week phase of fast AEL did not lead to additional improvements in strength, power, or speed. Indeed, previously realized improvements in speed may have been suppressed due to residual fatigue.

8.6 Practical Applications

The additional eccentric load afforded by slow AEL provides a superior stimulus to the neuromuscular system, a stimulus which may be especially relevant to trained athletes simultaneously attempting to increase strength, power, speed and aerobic fitness. While the improvements were generally of a small magnitude, these findings are nonetheless of interest to sport scientists and strength and conditioning practitioners given the short duration of the intervention, the training status of the subjects, and the inclusion of conflicting modalities that likely interfered with neuromuscular adaptation. As this method of training is highly taxing to the neuromuscular system, 8-weeks of AEL training may be inappropriate within a team sport setting unless a sufficient recovery period is available to realize performance responses.

Chapter 9

General Discussion

9.1 General Summary

The overall purpose of this thesis was to elucidate the role of eccentric muscle function and training in athletic performance. In addition to addressing identified gaps within the literature, the findings from this thesis were intended to have direct implications for practitioners. This purpose was addressed in four sections. Eccentric muscle function is thought to play an important role in human movement, and in particular, the execution of high force fast SSC tasks within athletic performance (e.g. the ability to tolerate large external forces and regulate leg spring stiffness during jumping and sprinting) [1-3]. However, following a comprehensive review of the literature comprising the first section of this thesis (Chapters 2 and 3) it was found that although chronic eccentric training has been demonstrated to induce greater increases in SSC performance and leg spring stiffness compared with other training modalities [62, 63, 226], there were no studies demonstrating a link between eccentric muscle function *per se* (i.e. maximum eccentric strength and eccentric muscle function under fast SSC conditions) and the performance of high force locomotive tasks such as jumping and sprinting in trained athletes. Identifying the role of eccentric muscle function in such tasks was proposed to have implications for the assessment and subsequent development of trained athletes (i.e. performance profiling and targeted training interventions). Furthermore, it was found that few studies investigating the effects of chronic eccentric training on athletic performance recruited resistance trained athletes participating in a broader physical preparation program. Therefore, it was proposed that determining the effects of varied tempo eccentric training on performance in trained athletes in an ecologically valid setting would have important implications for practitioners seeking to use this method of training in practice.

It remains difficult to assess eccentric muscle function during functional multi-articular movement in a practical environment with trained athletes [79]. The second section of this thesis therefore investigated the reliability of two novel assessment protocols that could be implemented in research and practical settings. The first protocol (Chapter 4) was an assessment of maximum lower body isoinertial eccentric strength using an eccentric back squat 1RM. Position-time data was used to identify an inability to control an isoinertial load at a consistent velocity in the lowering phase

of a back squat, and was proposed to minimize potential intra- and inter-rater error that may arise with the subjective evaluation of control alone [43, 80]. This method was successful in identifying a loss of control (i.e. a large increase in actual bar velocity) in the bottom third of the squat (i.e. 120-90°) at 105% of the eccentric 1RM in comparison to 100% of the eccentric 1RM. Actual bar velocity in the bottom third of the squat exhibited acceptable inter-day reliability at loads of 94%, 100% and 105% of the eccentric 1RM (CV: 5.3-11%; ICC: 0.63-0.70), and accordingly, the resulting eccentric 1RM identified with this method demonstrated high inter-session reliability (CV <1%; ICC >0.99). Therefore, this protocol was considered a reliable method of measuring maximal lower body isoinertial eccentric strength to be used in research and practical settings. An additional observation was that there were no clear changes in eccentric phase duration from 94% to 105% of the eccentric 1RM indicating that the subjective evaluation of tempo alone may not be sensitive enough to identify isoinertial eccentric failure. Finally, it was found that the eccentric back squat 1RM was 28% higher on average than the concentric back squat 1RM in resistance trained participants. The second protocol (Chapter 5) sought to investigate the inter-day reliability of braking and propulsive phase kinetic variables underpinning reactive strength in DJs performed across a range of heights typically implemented in research and practice (i.e. 0.25m, 0.50m and 0.75m). The analysis of the braking and propulsive phase kinetic variables underpinning DJ performance was proposed to provide insight into eccentric and concentric phase MTU contributions to high force fast SSC function. All performance variables (i.e. contact time, flight time, RSI and leg stiffness), and braking and propulsive phase kinetic variables (i.e. phase duration, force, power and impulse) exhibited acceptable reliability (CV: 2.5-11%; ICC: 0.38-0.97). The low relative reliability exhibited by braking impulse (i.e. ICC: 0.38-0.75) was expected due to the homogeneity of data resulting from standardised drop heights. A DJ phase analysis was therefore found to be a reliable method of assessing reactive strength (i.e. fast SSC function), and underlying braking and propulsive phase kinetic variables. Based on previous evidence [9, 11-13], it was proposed that this information provides insight into eccentric and concentric MTU contributions to fast SSC function. Therefore, this section identified reliable methods of assessing lower body eccentric strength and eccentric muscle function under fast SSC conditions that can be used within research and practical settings.

The third section investigated the role of eccentric muscle function in physical qualities relatively ubiquitous to athletic performance (i.e. reactive strength and maximum velocity sprinting capabilities [16, 325]) in two cross-sectional investigations utilizing the methods described in the preceding section. The first cross-sectional study (Chapter 6) investigated how eccentric muscle function contributed to fast SSC performance in highly trained sprinters in comparison to a non-sprint trained control group. Muscle function was inferred from braking and propulsive phase kinetic variables, while fast SSC function was inferred from reactive strength performance variables during DJs performed from a range of drop heights. As expected, trained sprinters exhibited a higher RSI versus non-sprint trained participants across all drop heights (ES: 3.11 ±0.86). Interestingly, this difference was primarily attained by briefer contact times (ES: -1.49 ±0.53) with smaller differences observed for flight time (ES: 0.53 ±0.58). Leg stiffness, braking and propulsive phase force and power were higher in trained sprint athletes. In particular, very large differences were observed in mean braking force (ES: 2.57 ±0.73) which was closely associated with contact time (r = -0.93). It was proposed that the greater reactive strength exhibited by trained sprint athletes reflected superior fast SSC function attained by a rapid and forceful eccentric muscle action, superior regulation of leg spring stiffness and an increased utilization of elastic structures [11, 14]. The second cross sectional investigation (Chapter 7) aimed to determine the role of isoinertial eccentric strength and eccentric muscle function under fast SSC conditions in stiffness regulation during maximum velocity sprinting in highly trained sprinters compared with trained team sport athletes. Trained sprinters attained a higher maximum sprinting velocity (ES: 1.54 ±0.85), briefer ground contact time (ES: -1.39 ±0.80) and higher modelled vertical stiffness (ES: 1.74 ±0.96) in comparison with team sport athletes. Trained sprinters also exhibited a moderately higher RSI (ES: 0.71 ±0.74) via the attainment of a briefer and more forceful ground contact phase, while only a possible small difference in isoinertial eccentric force (ES: 0.38 ±0.56) was found between the two groups. In addition, RSI demonstrated large to very large associations with maximum velocity (r = 0.72) and vertical stiffness (r = 0.67), whereas isoinertial eccentric force exhibited weaker correlations with maximum velocity (r = 0.56) and vertical stiffness (r = 0.41). A large association was also found between isoinertial eccentric strength and RSI (r = 0.60). Eccentric strength appears to contribute to vertical stiffness and maximum velocity sprinting speed in team sport

athletes and highly trained sprinters, but less so than reactive strength (i.e. fast SSC function). The stronger association between modelled stiffness regulation at maximum velocity and eccentric muscle function under fast SSC conditions (i.e. DJ mean braking force) compared with maximum isoinertial eccentric strength indicates that the regulation of lower body stiffness may be a task-specific motor strategy. The central nervous system may regulate the timing and magnitude of eccentric quasi-isometric muscle activation during sprinting to optimise the operating length and velocity of muscle fascicles, and maximise the utilization of elastic elements, as has been observed at slower running speeds [10]. Therefore, this section demonstrated that eccentric muscle function contributes to reactive strength and maximum velocity sprinting capabilities. However, it is apparent that eccentric muscle function under fast SSC conditions is a distinct quality to eccentric strength assessed under isoinertial conditions, and accordingly, appears to have a stronger association with the biomechanically similar ground contact phase of maximum velocity sprinting. This information is of substantial interest to the practitioner seeking to maximise the transfer of training methods to athletic performance enhancement.

The final section comprised a training study (Chapter 8) investigating the effects of an eccentric training intervention on athletic performance. This study determined the effects of a lower body resistance training program incorporating AEL in comparison with a TRAD resistance training program of an approximately equivalent IRV in resistance trained team sport (i.e. Rugby Union) athletes undertaking a broader physical preparation program. Two four-week phases of distinct eccentric phase tempos were compared (i.e. slow versus fast tempo). Strength, power, speed and muscle properties were assessed at baseline and following each training phase. It was found that the slow AEL protocol elicited superior improvements in back squat strength (ES: 0.48 ±0.34), 40m sprint performance (ES: -0.28 ±0.27), maximum sprinting velocity (ES: 0.52 ±0.34) and vertical stiffness at maximum velocity (ES: 1.12 ±0.72) versus slow TRAD training. In contrast, the second four week block of fast AEL training elicited a small increase in reactive strength (i.e. RSI via a moderate reduction in contact time), but impaired 40m speed and maximum sprinting velocity. In addition, fast TRAD (ES: -0.40 ±0.39) was superior in improving lower body power versus fast AEL. This study demonstrated that four weeks of AEL training with a slow eccentric tempo induced superior improvements in lower body strength,

maximum velocity sprinting speed and stiffness regulation in resistance trained athletes. However, a subsequent four-week phase of AEL training emphasizing fast eccentric tempo did not lead to additional improvements in strength and may have impaired maximum velocity sprinting capabilities. There was a possible improvement in reactive strength (i.e. fast SSC function) via a briefer ground contact time (i.e. likely reflecting an increase in braking phase force production [334]) with fast AEL training. This may have been due to the specific nature of the training stimulus. Nonetheless, it was proposed that the second period of eccentric training exceeded the recovery capabilities of the athletes undertaking a concurrent program. This information provides substantial insight into the effects of a varied tempo eccentric training protocol on athletic performance in resistance trained athletes participating in an ecologically valid physical preparation program.

This thesis has comprehensively reviewed the eccentric exercise and training literature and provided a strong rationale for the implementation of eccentric training for athletic performance. It has developed two novel methods of inferring eccentric muscle function during functional movement within a practical setting. These methods subsequently identified that eccentric muscle function is an important determinant of high force fast SSC function and leg spring stiffness regulation, which are relatively ubiquitous to athletic performance. Furthermore, the subsequent findings strongly suggested that the specific regulation of eccentric muscle function under task specific conditions may be more important to such tasks than maximal eccentric strength *per se*. Finally, it was found that eccentric training can improve athletic performance in resistance trained team sport athletes undertaking a concurrent training program, however, it should be incorporated judiciously.

9.2 Practical Applications

This thesis was intended to have direct implications for sports science and strength and conditioning practitioners working with highly trained athletes. Specifically, this research was designed such that findings could be readily implemented into the practice of HPSNZ practitioners delivering support services to elite New Zealand athletes. Several practical applications were identified:

1. Practitioners seeking to determine isoinertial eccentric strength of the hip and knee extensors in a practical setting can reliably assess an eccentric back squat 1RM using a smith machine and a linear position transducer. Given the inability of eccentric phase duration to identify eccentric failure, the approach which has been reported in previous research [43, 80] is not recommended.

2. If eccentric strength cannot be assessed, practitioners seeking to implement an eccentrically emphasised back squat training protocol in resistance trained males are recommended to use loads approximately 28% greater than the concentric back squat 1RM, particularly if large ranges of motion and controlled tempos are intended.

3. Braking and propulsive phase kinetic data from a reactive strength task (i.e. a DJ) are proposed to provide insight into the eccentric and concentric MTU contributions to fast SSC function. Therefore, the use of a force platform may provide useful insight into individual athlete strengths (e.g. a rapid generation of propulsive/concentric force and therefore higher flight time) and weaknesses (e.g. an inability to apply large braking/eccentric forces to arrest the downward velocity of the centre of mass, and therefore a slower contact time) within reactive strength tasks.

4. It is acknowledged that force platforms with adequate sampling rates (i.e. 1000 Hz) and ad hoc analysis software are not always accessible within practical settings. Therefore, it is proposed that due to the almost perfect correlation between mean braking force and contact time during DJs performed from a range of drop heights, contact time (e.g. assessed from a contact mat) can be used as a proxy measure of braking force during a DJ. A reduction in contact time (i.e. without compromising flight time) from a standardised drop height may therefore reflect enhanced reactive strength performance via improved eccentric muscle function.

5. Practitioners should be aware that with increasing DJ drop height from 0.25m to 0.75m, an unconscious adjustment in stepping technique may occur irrespective

of training status. This appears to result in a continuous discrepancy between actual and intended drop heights. Therefore, athletes should be repeatedly cued to avoid stepping down from the box at higher drop heights, or the use of box heights above the intended drop height should be implemented.

6. As identified in chapters 6 and 7, high levels of reactive strength exhibited by highly trained sprint athletes appear to be largely underpinned by the ability to strike the ground with a stiffer leg spring, and the production of more force in a briefer ground contact time. As a briefer ground contact time is primarily determined by the rapid application of large braking forces, training interventions which emphasise the rapid application of braking forces (i.e. fast contact plyometric training, and eccentrically emphasised resistance and plyometric training methods) are proposed to maximise improvements in reactive strength. This proposition is supported by the findings in chapter 8 which demonstrated an improvement in contact time and reactive strength in Rugby Union athletes utilizing such training methods. It should be acknowledged that well developed concentric MTU function (i.e. RFD) is likely critical in the attainment of sufficient propulsive impulse (i.e. to attain a given flight time or jump height) during a brief ground contact phase. Therefore, the enhancement of braking phase characteristics should be emphasised, but not developed in isolation at the risk of compromising propulsive phase characteristics.

7. The regulation of leg spring stiffness to effectively absorb and return large vertical ground reaction forces during high force locomotive tasks (i.e. jumping and sprinting) appears to be influenced by eccentric muscle function. However, as identified in chapter 7, eccentric muscle function under fast SSC conditions exhibited a stronger relationship with stiffness regulation at maximum velocity than isoinertial eccentric strength. While lower body eccentric strength appears to contribute to both reactive strength and stiffness regulation during sprinting, the regulation of eccentric muscle function under task-specific conditions appears to be a somewhat distinct quality. Therefore, practitioners seeking to improve stiffness regulation during maximum velocity sprinting (and therefore sprinting performance) in trained athletes should prioritise specific maximum

velocity sprint training. Athletes may need to develop an appropriate technical model that allows them to strike the ground with a sufficiently stiff leg spring and maximise vertical ground reaction force production; the timing and magnitude of the eccentric (and/or quasi-isometric) muscle action under such conditions may be a task specific motor skill [10, 15]. Exposure to large vertical ground reaction forces via maximum velocity sprint running and overloaded sprinting drills (e.g. barbell or medicine ball loaded drills, skips and bounds) may most effectively enhance leg spring stiffness regulation during sprinting [18].

8. Developing maximal eccentric strength and eccentric muscle function under fast SSC conditions (i.e. within a reactive strength task such as a DJ) is also proposed to aid stiffness regulation at maximum velocity in trained athletes. This proposition is supported by the findings in study 8 which demonstrated that eccentrically emphasised resistance training improved maximum velocity sprinting speed and stiffness regulation in Rugby Union athletes. It is less clear how this form of training would influence maximum velocity sprinting capabilities in highly trained sprint athletes. Nonetheless, training methods that develop eccentric muscle function are likely a useful adjunct to specific maximum velocity sprint training.

9. Eccentrically emphasised resistance training can be successfully implemented into the program of trained team sport athletes completing a concurrent training program. Four-weeks of slow tempo AEL training of a relatively modest volume (i.e. one AEL maximum strength exercise performed twice per week, and two AEL power exercises performed once per week integrated into a standard TRAD training protocol) is effective in rapidly increasing lower body strength, maximum velocity sprint performance and leg spring stiffness regulation in trained Rugby Union athletes. Given the lack of clear increases in lower body hypertrophy or power, improvements observed were likely underpinned by enhancements in neural drive, and speculatively, changes in passive stiffness properties of elastic tissue (e.g. tendon, fascia and titin).

10. The inclusion of extended periods of eccentric training (i.e. 8-weeks) and/or fast tempo eccentric training may be an inappropriate training strategy in trained team sport athletes undertaking a concurrent training program. Extended periods of eccentric training may exceed the recovery capacity of trained Rugby Union athletes completing conflicting training units. It is possible that such a periodization strategy is warranted to maximise neuromuscular performance in Rugby Union athletes that have a sufficient period of time to taper before a competition, or athlete populations not attempting to concurrently develop disparate (i.e. aerobic power) components of fitness (e.g. track and field sprint athletes).

9.3 Limitations

A strength of this thesis is the directly applicable nature of these findings to practice, however several limitations arose due largely to the applied nature of the research. It remains difficult to assess eccentric muscle function *in vivo* during functional multi-articular movement. At present, such investigations generally (e.g. [9-12]) involve the determination of muscle fascicle behaviour via continuous ultrasound, muscle activation and reflex input (e.g. Golgi-tendon organ inhibition and short latency stretch reflex potentiation from muscle spindles) from EMG recordings, and external force production via force platform technology or isokinetic dynamometry. In addition, measuring *in vivo* force production of individual MTUs requires extremely invasive methods (i.e. buckle transducers or optic fibres surgically inserted into the MTU) [14, 15]. This methodology has been used within research settings to assess MTU dynamics across a range of tasks, and has provided useful insight into muscle function during human movement. However, as it stands, these procedures cannot be used within certain performance tasks (e.g. maximum velocity sprinting) and are inaccessible within a practical (i.e. ecologically valid) environment. Therefore, questions pertinent to the performance of highly trained athletes remain unanswered.

Subsequently, two novel assessments of eccentric muscle function were developed within this thesis, the limitations of which are acknowledged:

1. The isoinertial eccentric back squat used within chapters 4 and 7 measured the eccentric strength of hip and knee extensors over a large range of motion (i.e. 0-90° at the knee joint) at a relatively slow contraction speed (i.e. ~30°/s). This was necessary to identify a clear failure to control the load during the descent. Therefore, this assessment may not reflect the nature of maximum eccentric strength expressed during specific athletic performance tasks (i.e. shorter ranges of motion and faster contraction speeds). In addition, this assessment does not measure eccentric strength of the plantar flexors which likely contributes to fast SSC function within high force locomotive tasks.

2. The DJ phase analysis used to infer eccentric muscle function under fast SSC conditions in chapters 5, 6 and 7 did not measure eccentric MTU behaviour *in vivo*. Based upon previous research [9, 11-13], this approach assumed that braking phase kinetic variables reflected underlying eccentric MTU behaviour within a SSC (e.g. braking force reflected a more forceful eccentric contraction). Nonetheless, the point may be made that irrespective of the MTU mechanisms underpinning braking force (e.g. eccentric versus isometric muscle fascicle behaviour), braking force as a mechanical construct has been clearly implicated as an important determinant of reactive strength and maximum velocity sprinting performance within this thesis. The use of a single force platform allowed the determination of performance measures and vertical ground reaction forces, but did not identify the role of joint kinematics in DJ performance. As noted in chapter 6, there was a consistent discrepancy between the intended DJ drop height and predicted drop height using the impulse-momentum principle. Given that this was observed across all participants irrespective of training status, it is proposed that this does not influence the interpretation of the observed findings (i.e. differences between groups). Braking impulse was measured during DJs performed from 0.50m in chapters 7 and 8, but not reported. A similar effect was observed but remained across all participants and therefore not considered to influence the results.

The limitations with experimental studies investigating the role of eccentric muscle function and training in athletic performance include:

1. The cross-sectional experimental designs used within chapters 6 and 7 may restrict the interpretation and subsequent extrapolation of findings. As cross-sectional designs assessing the differences between two athlete and non-athlete samples (i.e. highly trained sprinters versus non-sprint trained participants in chapter 6, and highly trained sprinters versus trained team sport athletes in chapter 7), caution should be made extrapolating these findings to athlete populations of differing characteristics. It is possible that the magnitude of differences (i.e. in group means) between the groups, and therefore assumed importance of selected variables, were an artefact of the participant cohorts sampled. For example, the importance of a brief contact time in reactive strength performance in chapter 6 may have been influenced by other characteristics or covariates inherent to the highly trained sprinters recruited (e.g. technique, neuromuscular activation and MTU properties not measured). In addition, while strong associations were identified between measures of eccentric muscle function and athletic performance, causation cannot be assumed using simple correlational analyses alone. It cannot be ruled out that additional variables not measured within these investigations contributed to (e.g. mediated) the observed associations. Nonetheless, it should be acknowledged that with the exception of height in chapter 7, intrinsic participant characteristics (e.g. age, body mass and sex) thought to mediate an effect on the variables measured were matched, and therefore controlled for, between groups.

2. Although female participants were included within chapters 5, 6 and 7, menstrual cycle status was not measured nor controlled for. It is possible that female sex hormones influenced the stiffness status of the participants within these investigations. Indeed, previous research has identified menstrual cycle hormonal fluctuations to exert an effect on collagen synthesis rates [368] and the passive stiffness of knee ligaments such as the ACL [369]. It has been found that leg stiffness, as determined from single leg hopping, can vary by as much as 9% from the ovulatory phase to the follicular phase of the menstrual cycle in adolescent Netball athletes [370]. Therefore, it should be acknowledged that the menstrual cycle status of the female participants recruited within this thesis may have contributed some non-systematic error to the reported findings. However, it should be noted that several investigations have failed to identify an effect of

menstrual cycle hormonal fluctuations on tendon stiffness or muscle stiffness in healthy young adult women [371-374], and therefore further research is warranted to determine if this is a mechanism of concern for the practitioner.

3. The sample sizes for both cross-sectional investigations ($n = 24$) were selected to balance study power with practicality. The number of highly trained sprinters within New Zealand is limited, and those recruited in the present thesis ($n = 12$ and $n = 11$ for chapters 6 and 7, respectively) were among the best in the country (i.e. including national champions who had attended Commonwealth Games, Olympic Games and World Championships). Therefore, the participant characteristics were considered a greater priority in investigating questions related to elite New Zealand athlete performance than sample size. Nonetheless, it is still acknowledged that both cross-sectional investigations were underpowered to confidently determine likely meaningful effects of a small to moderate magnitude. Using maximum chances (%) of clinical error for Type I (i.e. α): 0.5 and Type II (i.e. β): 25, respectively, and a SWC of 0.20 multiplied by the pooled between-participant SD, a sample size of 24 provides sufficient power to confidently detect a very likely ES of 0.95 or higher and a Pearson correlation (r) of 0.35 or higher [375]. Therefore, the small sample sizes used may have compromised the ability to confidently detect ES values (i.e. small and some moderate ES differences) and correlations below these thresholds. Nonetheless, most ES statistics of interest, and all correlations of interest, within both cross-sectional investigations exceeded these thresholds. In addition, the statistical analysis used (i.e. magnitude based inferences) allowed the qualitative inference of the likelihood of the observed effect (i.e. including those below the aforementioned threshold), given the breadth of the associated confidence interval [280, 376].

4. There were several methodological limitations within the training study in chapter 8. While attempts were made to match the baseline characteristics between groups in the training study, baseline differences between groups were apparent following attrition ($n = 3$). Subjects within the AEL group were moderately more powerful and faster than the TRAD group, and this may have partly mediated the training responses of several variables and subsequently

confounded the effects of the training protocol. As noted within chapter 8, it is possible that these baseline differences attenuated rather than enhanced the effects of the AEL protocol. In addition, only a single periodization model was tested (i.e. slow tempo AEL and TRAD training at lighter loads followed by fast tempo AEL and TRAD training at higher loads) and therefore it is not clear whether the reported findings were due to tempo and loading *per se*, or the order of the training phases. It was difficult to account for all contextual variables (e.g. running load, contact load, nutrition and recovery practices) in 14 participants over 12 weeks within an applied sporting environment. It is unclear how these additional variables contributed to the reported findings. Nonetheless, it is proposed that these limitations were a necessary trade-off to maximize the ecological validity and subsequent practical implications of the study. It should be acknowledged the limitations of using isoinertial loading to achieve AEL within this chapter. A standardised eccentric load and movement velocity across the intended range of motion is not guaranteed with isoinertial loading in contrast to isokinetic options. This may have contributed to the discrepancies between the findings in chapter 8 and previous research using fast isokinetic eccentric training. Finally, as an applied investigation recruiting trained athletes it was not possible to take extensive measures (e.g. the recording of EMG during the back squat to determine the role neuromuscular activation in strength changes) or invasive measures (e.g. muscle biopsies to determine the influence of MHC isoform and titin changes on measures of speed and power) to identify mechanistic factors underpinning performance changes.

5. The sample size in the longitudinal training study in chapter 8 was constrained by the number of participants available in the training squad ($n = 14$ following attrition). As noted, the priority of this research was to recruit a trained athlete population completing an ecologically valid physical preparation program such that findings would be directly applicable to elite athlete preparation within HPSNZ. While the study design used (i.e. parallel groups controlled trial) would have benefited study power, it is possible that the investigation was underpowered to detect likely small effects. For example, using the relative back squat 1RM, maximum chances (%) of clinical error for Type I (i.e. α): 0.5 and Type II (i.e. β): 25, respectively, a SWC of 0.20 multiplied by the pooled

between-participant SD (i.e. 0.05 kg·BM^{-1}), and the TEM (i.e. 0.09 kg·BM^{-1} based upon a CV of 5%), a sample size of 14 provided sufficient power to detect a likely change of 0.15 kg·BM^{-1}, and therefore, an ES of 0.62 (i.e. a moderate effect) or higher [375]. Therefore, while several small effects were observed between groups, it is possible that the 'true' differences between AEL and TRAD training protocols were larger than those detected, and subsequently reported. While caution should be made extrapolating these findings to larger athlete samples, the inclusion of confidence intervals and qualitative inferences does provide the researcher or practitioner with insight into the likelihood that the reported effects are representative of what would be found in the broader Rugby Union population under similar contextual conditions [376].

9.4 Future Research Directions

While several gaps within the literature and practical questions were addressed in the present thesis, there remains scope for future research. Future research should investigate methods of assessing eccentric muscle function that combines the strengths of methods used within both research and practical settings. An assessment of eccentric strength under functional multi-articular conditions (e.g. back squat, hip thrust, calf raise, bench press and bench row) combining isokinetic technology with a smith machine would be of substantial interest to researchers and practitioners alike. Such methodologies could provide insight into eccentric strength at various ranges of motion in different movements and at different contraction velocities. This would therefore, provide more detailed insight into the role of eccentric muscle function under conditions more closely replicating athletic performance tasks. Methods of assessing MTU behaviour *in vivo* during athletic performance tasks such as sprinting would be of substantial interest to the field. Specifically, the determination of muscle function in leg spring stiffness regulation and maximum velocity sprinting would allow researchers and practitioners to identify the limiting factors of this aspect of sprint performance. This information would have useful implications for athletic testing and the implementation of targeted training methods. Nonetheless, this research direction is constrained by current technological limitations rather than a lack of interest *per se*. There is substantial scope to investigate applied eccentric training interventions on athletic performance in

different trained athlete populations. It is clear that eccentrically emphasised training exerts a marked effect on neuromuscular performance; however, it remains unclear how to best manipulate volume, intensity, tempo, frequency and exercise selection to maximise athletic performance in trained athletes. In addition, investigations should elucidate the role of tapering practices following eccentric training to more clearly describe the apparent delayed training effect with this method of training. Finally, as per any area of scientific investigation, there would be substantial utility in attempting to replicate the findings within the present thesis using the methodology described, and larger sample sizes. It is argued that the investigations were diligently conducted and represent a high standard of scientific rigour given the aforementioned constraints of applied research; however, inductive inferences from single studies recruiting small samples of athletes should be made with caution. Future research is warranted to further elucidate the role of eccentric muscle function and training in athletic performance.

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Appendices

Appendix 1: Ethical Approval Form

AUTEC Secretariat

Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

16 March 2016

Mike McGuigan
Faculty of Health and Environmental Sciences

Dear Mike

Re Ethics Application: 16/51 Eccentric training and elite athlete performance.

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 15 March 2019.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 15 March 2019;

- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 15 March 2019 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Kate O'Connor
Executive Secretary
Auckland University of Technology Ethics Committee

Cc: Jamie Douglas j.w.douglas@live.com, Angus Ross; Simon Pearson

Appendix 2: Consent Forms

Appendix 2.A. Consent Form 1 (applicable to chapters 4, 5 and 6).

Consent Form

AUT
TE WĀNANGA ARONUI
O TĀMAKI MAKAU RAU

Project title: **The Development of a Protocol to Assess Eccentric Muscle Mechanical Function.**

Project Supervisor: **Professor Mike McGuigan**

Researcher: **Jamie Douglas**

○   I have read and understood the information provided about this research project in the Information Sheet dated 16 February 2016.

○   I have had an opportunity to ask questions and to have them answered.

○   I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

○   I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance, or any infection.

○   I agree to take part in this research.

○   I agree to my performance testing results to be released to my coach (please tick one): Yes○ No○

○   I wish to personally receive a copy of my performance testing results but I do not wish my coach to receive a copy (please tick one): Yes○ No○

○   I wish to receive a copy of the report from the research (please tick one): Yes○ No○

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on 16/03/2016 AUTEC Reference number 16/51.

Note: The Participant should retain a copy of this form.

Appendix 2.B. Consent Form 2 (applicable to chapter 7).

Consent Form

Project title: **The Relationship between Eccentric Muscle Mechanical Function and Maximum Velocity Sprint Performance.**

Project Supervisor: **Professor Mike McGuigan**

Researcher: **Jamie Douglas**

○   I have read and understood the information provided about this research project in the Information Sheet dated 16 February 2016.

○   I have had an opportunity to ask questions and to have them answered.

○   I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

○   I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance, or any infection.

○   I agree to take part in this research.

○   I agree to my performance testing results to be released to my coach (please tick one): Yes○ No○

○   I wish to receive a copy of the report from the research (please tick one): Yes○ No○

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on 16/03/2016 *AUTEC Reference number* 16/51.

Note: The Participant should retain a copy of this form.

Appendix 2.C. Consent Form 3 (applicable to chapter 8).

Consent Form

Project title: **The Effects of Fast and Slow Eccentric Training on Muscle Properties and Sprint Performance in Trained Athletes.**

Project Supervisor: **Professor Mike McGuigan**

Researcher: **Jamie Douglas**

○   I have read and understood the information provided about this research project in the Information Sheet dated 16 February 2016.

○   I have had an opportunity to ask questions and to have them answered.

○   I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

○   I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance, or any infection.

○   I agree to take part in this research.

○   I agree to my performance testing results to be released to my coach (please tick one): Yes○ No○

○   I wish to receive a copy of the report from the research (please tick one): Yes○ No○

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on 16/03/2016 *AUTEC Reference number* **16/51.**

Note: The Participant should retain a copy of this form.