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The Application of Novel High-Intensity Eccentric Exercise: Evolving High-Performance Strength and Conditioning Practice

Mellissa Harden

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No part of this thesis has been submitted in the past or is to be submitted for any degree at any other University.

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Abstract

Habitual use of high-intensity eccentric exercise increases the potential for muscle to be stronger and faster, and therefore generate more power. The application of high-intensity eccentric training in a performance environment is fraught with problems. This has restricted the potential to understand training prescription and adaptation in applied settings and performance contexts. The overarching aim of this thesis was to better understand the application of novel high-intensity eccentric exercise in a high-performance context, in a manner that is relevant to strength and conditioning (S&C) practitioners.

The first investigation (Chapter 3) was exploratory in nature and acquired experiential knowledge from high-performance S&C practitioners which inspired the development of the series of investigations for this work. The second investigation (Chapter 4) provided a better understanding of the functioning of a bespoke leg press device and provided preliminary insight into the different mechanical stimuli that can be offered when exercising using the device in a conventional, isometric or an eccentric manner. The third and fourth investigations provided new insight into the typical performance responses of strength-trained individuals during isometric assessment (Chapter 5) and high-intensity eccentric repetitions (Chapter 6). These investigations highlighted the potential for force output during different tasks performed on the leg press device. The fifth investigation (Chapter 7) captured the immediate training-induced effects of high-intensity eccentric exercise and raised awareness of the individual variability in the responses to this type of exercise. The outcomes provided information which could assist with the organisation and management of the training stimulus (or a similar) within a broader physical preparation programme. Importantly, the results highlighted a potential issue with using isometric force output as a basis for prescribing eccentric training loads. Consequently, a task-specific assessment of eccentric strength was developed in the sixth investigation (Chapter 8) to establish a more definitive evaluation of eccentric strength and to provide a more accurate platform to prescribe individualised eccentric training loads.

The task-specific approach to eccentric load prescription was applied in the seventh investigation (Chapter 9) to prescribe exercise for a 4-week strength training intervention. This approach to training load prescription was well-tolerated over the course of the training intervention. The data provided an indication of the potential characteristic response to the prescribed exercise and implied that for some individuals, the task-specific approach to eccentric load prescription could be a marginally more efficient method of training. Although a more definitive conclusion could have been drawn had the training period continued for a longer duration and included a greater number of sessions. Importantly, the elite athlete group demonstrated a distinct response and perhaps have a different tolerance for the prescribed exercise. Overall, this work addressed the prescription, evaluation and application of novel high-intensity eccentric exercise and offered an insight into the potential adaptations in strength-trained individuals and elite sprint cycling athletes. The information was intended to contribute towards the body of scientific knowledge pertaining to eccentric training, whilst assisting S&C coaches with the application of eccentric exercise with athletes.

Publications

The following peer reviewed publications resulted from this work:

Arising from Chapter 5:

Harden, M., Wolf, A., Hicks, K.M. and Howatson, G. (2018). Familiarisation, reproducibility, sensitivity and joint angle specificity of bilateral isometric force exertions during leg press. *Isokinetics in Exercise Science*. 26(4): 291-298.

Arising from Chapter 6:

Harden, M., Wolf, A., Russell, M., Hicks, K.M., French, D. and Howatson, G. (2018). An evaluation of supramaximally loaded eccentric leg press exercise. *Journal of Strength and Conditioning Research*. 32(10): 2708-2714.

Arising from Chapter 8:

Harden, M., Wolf, A., Haff, G.G., Hicks, K.M. and Howatson, G. (2019). Repeatability and specificity of eccentric force output and the implications for eccentric training load prescription. *Journal of Strength and Conditioning Research*. 33(3): 676-683.

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List of Abbreviations

The following abbreviations have been defined in the text in the first instance.

CI	Confidence interval
CMJ	Countermovement jump
CMVC	Concentric maximum voluntary contraction
CO	Concentric-only
CON_{1RM}	Concentric 1 repetition maximum
CSA	Cross sectional area
CV	Coefficient of variation
DIST	Distal portion of the muscle
ECC_{1RM}	Eccentric 1 repetition maximum
EIMD	Exercise induced muscle damage
EMVC	Eccentric maximum voluntary contraction
EO	Eccentric-only
FL	Fascicle length
ICC	Intraclass correlation coefficient
IMVC	Isometric maximum voluntary contraction
ISO_{120}	Isometric voluntary contraction at 120° knee joint angle
ISO_{90}	Isometric voluntary contraction at 90° knee joint angle
LLM	Lean leg mass
MID	Mid portion of the muscle
PA	Pennation angle
RFD	Rate of force development
RM	Repetition maximum
ROM	Range of movement
S&C	Strength and conditioning
SJ	Squat jump
SSC	Stretch shortening cycle
SWC	Smallest worthwhile change
$TRAD_{1RM}$	1 RM during a coupled eccentric-concentric action
TUT	Time under tension
VL	Vastus lateralis

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To the Thompson's, I dedicate this work to you.

Declaration

I declare that the work contained in this thesis has not been submitted for any other award. I confirm that it is all my own work and fully acknowledges opinions, ideas and contributions from the work of others.

All work included in this thesis has received ethical approval from the Faculty Ethics Committee at Northumbria University.

I declare that the Word Count of this Thesis is 46771 words.

Name: Mellissa Harden

Signature:

Date: 01/04/2019

Chapter 1

Introduction

1.1 Background

Resistance training can improve a multitude of neuromuscular and morphological qualities which are relevant to athletic performance across a wide range of sporting disciplines (Suchomel *et al*., 2016). When structured in a progressive manner, resistance training programs can optimise an individual's force producing capacity (DeWeese *et al*., 2015a) and decrease the risk of injury (Lauersen *et al*., 2014). However, as an athletes training experience grows it becomes increasingly more difficult to continually stimulate neuromuscular adaptation, even with structured and progressive loading regimes (Baker, 2013; Häkkinen *et al*., 1987). When working with athletes who have a high training age and a wealth of experience using resistance exercise, coaches must offer greater training variety and more complex loading paradigms using novel approaches to provide a stimulus potent enough to continue neuromuscular development and nurture long-term progression of athletic performance (Bompa and Haff, 2009).

High-intensity eccentric training is considered an appropriate means to offer strength-trained individuals and athletes a stimulus that is potent enough to nurture the progression of neuromuscular qualties. The unique neural control strategies (Enoka, 1996a) and distinct mechanical processes (Lieber, 2018) underpinning lengthening muscle actions, which occur during eccentric training, makes it possible to generate very high muscle tension and force output. When under high-intensity conditions, the magnitude of muscle tension and force output can exceed what can be achieved with traditional resistance training approaches (Franchi *et al*., 2014; Hollander *et al*., 2007). There is a wealth of evidence to suggest that habitual use of high-intensity eccentric exercise; reduces neural inhibition (Aagaard, 2018); increases agonist neural drive and decreases co-activation of antagonists muscles (Seger and Thorstensson, 2005); facilitates the recruitment of type II motor units (Friedmann-Bette *et al*., 2010a; Hortobágyi *et al*., 1996a), shifts the muscle towards a faster phenotype (Friedmann-Bette *et al*., 2010a; Hortobágyi *et al*., 1996a), stimulates a distinct myogenic response for architectural remodelling (Franchi *et al*., 2014), increases eccentric, isometric and concentric force capacity (Cadore *et al*., 2014; Higbie *et al*., 1996; Hortobágyi *et al*., 1996a) and enlarges muscle cross-sectional area (CSA, Bogdanis *et al*., 2018). These adaptive responses imply a stronger, larger, faster muscle with the potential to generate more power (Aagaard, 2010). Given the nature of these adaptations there is a great deal of interest in this mode of training from athletes, coaches and S&C practitioners. Especially, those who operate within strength-power based sports where maximal strength, muscle mass and absolute power output are key determinants of performance.

Conventionally, exercise involves coupled eccentric-concentric movement comprising of a descending and ascending phase, respectively. The same absolute load is used for both phases of the exercise, whereby the prescription of external load is based on strength capacity during the lifting (ascending) phase of the exercise. Resistance training in this manner overlooks the force generating potential of eccentric muscle actions. To fulfil the greater force producing capacity innate to eccentric muscle actions, it is necessary to apply greater load during the descending phase of an exercise. Unfortunately, the application of adequate load in a performance environment is fraught with problems. The logistical constraints and limitations associated with this approach have led to a paucity of information about this activity in an applied context. This has limited the potential to understand the application of high-intensity eccentric exercise for training prescription and adaptation in an athletic context.

As mentioned, the application of very high loads during the descending phase of an exercise is likely to provide a novel and potent stimulus, even for the experienced athlete. Therefore, it is important for research to address the relevant gaps in existing eccentric exercise research and applied practice to establish relevant and efficacious methods for applying high-intensity eccentric exercise as a means to support neuromuscular adaptation and to nurture the progression of athletic performance.

1.2 Gaps in the Literature

A vast majority of the eccentric training literature employs untrained or moderately trained populations, whereby few investigations have used a well strength-trained or athletic populations (Douglas *et al*., 2017). It is likely that well strength-trained or athletic populations will tolerate exercise stimulus differently than untrained or moderately trained populations (Baker, 2013). For this reason, the adaptive responses observed in studies that have recruited untrained or resistance trained naïve individuals are unlikely to be an accurate representation of the adaptive responses presented by strength-trained individuals and athletes. To ensure outcomes are more applicable to athlete groups, research needs to be conducted using strength-trained individuals and, ideally, athletes.

Many training interventions comprise of regimes which utilise isokinetic eccentric exercise. Different mechanical constraints are offered by isokinetic and isotonic eccentric exercise, which can result in different adaptive responses (Coratella *et al*., 2015; Doguet *et al*., 2016; Guilhem *et al*., 2010). Therefore, researchers and practitioners must be cautious when making inferences from research that has utilised isokinetic means, particularly when the intention is to implement habitual eccentric exercise using isotonic means. To add, isokinetic exercise is performed at a constant angular velocity and is far removed from the demands imposed during typical human movement, which demands an interplay of acceleration and deceleration. In the endeavour to positively impact sports performance, isotonic eccentric exercise may be more appropriate given that the conditions are more closely related to typical movement.

Investigators have tended to implement eccentric training models that are far removed from the progressive and systematic organisation of an athlete's strength training programme. For example, using exercise programmes for extended periods of time (Reeves *et al*., 2009), using isolated muscle actions and single joint exercise (Vikne *et al*., 2006), administering an eccentric stimulus in isolation rather than being incorporated into a more comprehensive training programme (Franchi *et al*., 2014), or to specifically induce fatigue and muscle damage (Howatson *et al*., 2007). Research of this nature has undoubtedly provided valuable insight into the mechanisms underpinning the response to eccentric exercise. Although, S&C practitioners might struggle to readily utilise the information in their practice as the application is likely to be inappropriate in the context of the high-performance athlete. Recently, this has been recognised and researchers have implemented more ecologically valid protocol (Cook *et al*., 2013; Douglas *et al*., 2018). However, in order to substantiate the use of eccentric exercise for athletic performance enhancement, researchers must continue to bridge the gap between science and practice. Therefore, procedures and programme content must be scientifically rigorous but be developed with practical applicability in mind.

Given that neuromuscular and morphological qualities affect muscle function it is important that investigations appreciate both neuromuscular and morphological consequences of performing eccentric training. Research has provided some insight into the effects of eccentric exercise on different aspects of physical performance and morphology (Baroni *et al*., 2013; Coratella *et al*., 2018). Continuing to conduct research of this nature will provide a better understanding of the responses to different eccentric training regimes and enable more accurate evaluation of the efficacy of eccentric exercise for enhancing neuromuscular function.

1.3 Aims of the Thesis

Overall, S&C practitioners can make inference from the available literature, but it is difficult to make full use of the information given the disparity in application, protocol and evaluation processes. Furthermore, the predominant use of untrained or moderately trained individuals and isolated single-joint exercise limits the transferability of procedures and outcomes to athletic populations and applied contexts. As a result, there are elements of ambiguity surrounding the use of eccentric exercise in applied practice which can be off-putting for S&C practitioners.

Consequently, the overarching aim of this thesis was to understand the application of novel high-intensity eccentric exercise in a performance context. The information was intended to contribute towards the body of knowledge pertaining to eccentric training science, whilst assisting S&C coaches with the use of eccentric exercise with their athletes. Specifically, this work comprised of seven experimental chapters which correspond the following seven aims:

1) To gain an insight into what S&C practitioners know and use regarding eccentric resistance training for the high-performance athlete
2) To evaluate the function and use of a bespoke leg press device designed for strength training and research
3) To evaluate the efficacy of isometric strength assessment performed on a leg press device
4) To evaluate the mechanical response to high-intensity eccentric exercise and understand how it alters with changing conditions
5) To gain an insight into the immediate exercise-induced alteration in muscle function and muscle ultrastructure following an initial and repeated bout of high-intensity eccentric resistance exercise
6) To determine the repeatability and specificity of eccentric force output and assess the methodological accuracy when using non-specific measures of strength to prescribe eccentric training loads
7) To ascertain the feasibility of a strength training programme which incorporates a progressive, task-specific approach to eccentric load prescription.

Chapter 2

Literature Review

2.1 Introduction

This literature review will address the unique physiological features of eccentric muscle actions and the significance of these actions in athletic endeavours. Following this, the practical application of high-intensity eccentric exercise will be discussed with reference to load prescription and the application of load in an applied context. There will be a discussion of the literature pertaining to the performance responses following habitual use of high-intensity eccentric exercise, and recognition of the neural and morphological mechanisms which underpin these performance responses. Penultimately, the propensity of exercise-induced muscle damage (EIMD) and fatigue following the performance of high-intensity eccentric exercise will be considered, as this can have implications for exercise prescription and organisation of an eccentric training stimulus within an athlete's physical preparation programme. Finally, the overarching aim of the thesis and the specific aims underpinning this will be identified.

2.2 Physiological Features of Eccentric Muscle Actions

An eccentric muscle action occurs when the force generated by the muscle is less than the force imposed by the external load which results in muscle lengthening whilst under tension (Nishikawa, 2016). The characteristics of eccentric muscle actions are fundamentally different compared to concentric and isometric actions; a concept that has been acknowledged by several researchers (Bigland-Ritchie and Woods, 1976; Duchateau and Baudry, 2013; Duchateau and Enoka, 2016; Enoka, 1996a; Herzog, 2018; Nishikawa, 2016). The purpose of this section is to address the overarching unique neural, mechanical and metabolic characteristics associated with eccentric muscle actions which supports the application of atypical resistance exercise that accentuates loading during eccentric muscle actions.

2.2.1 Mechanical Characteristics

Force output is greater during eccentric muscle actions compared to isometric and concentric (Hortobágyi *et al*., 1996b). From a mechanical perspective, this observation cannot be fully explained with the sliding filament and cross-bridge theories which apply to concentric and isometric contraction (Herzog, 2014). Conventionally, the muscle performs work following calcium influx from the sarcoplasmic reticulum. Calcium binds to troponin to remove tropomyosin from myosin binding sites. The hydrolysis of ATP causes one of the dual heads of the myosin filament to bind to the site and form a cross-bridge. The myosin head pivots to slide the actin filament towards the centre of the sarcomere and releasing ADP and inorganic phosphate. The myosin head dissociates from actin upon binding another ATP molecule. When activation ceases, the sarcoplasmic reticulum reuptakes calcium and the inhibitory action of the troponin-tropomyosin complex is restored (McArdle *et al*., 2010). The number of cross-bridge attachments at a given time determines muscle force output. This depends on factors such as; the magnitude of neural activation and intracellular calcium concentration, the length of filament overlap, i.e. length-tension relationship, and the time available for cross-bridge cycling, i.e. force-velocity relationship (Jones, 2004).

This process does not fully address the mechanics of eccentric muscle actions. Uniquely, forcible lengthening of the muscle induces high strain which can result in cross-bridges detaching in absence of ATP splitting and without completing a conventional cross-bridge cycle (Jones, 2004). After forcible detachment, myosin filaments remain in an active state for rapid reattachment back to actin (Lombardi and Piazzesi, 1990). With sustained and/or fast strain, the second head of myosin is activated and docks to the actin filament causing a greater number of attached cross-bridges at a given time (Linari *et al*., 2000). Consequently, the unique mechanics underpinning eccentric muscle actions increases cross-bridge force.

Further contributing to force enhancement during eccentric muscle actions, structural elements within the sarcomere increase in stiffness upon muscle activation. Nishikawa (2016) states that upon calcium influx, titin is activated. Specifically, the N2A region of titin binds to actin. The N2A region is located between compliant tandem immunoglobulin (Ig) domains and the stiffer PEVK region Figure 2.2.1. Binding of the N2A region to actin eliminates the compliance from the proximal tandem Ig domain for the stiffer PEVK region to take up the slack. The inherent stiffness provides the potential to produce much higher force. Furthermore, Nishikawa (2016) proposed the winding filament hypothesis which states that during active force development, the rotary action of the cross-bridges causes the PEVK segment to wind around actin. Collectively, these actions increase the stiffness of titin upon calcium influx to provide force that is directly proportional to its length. A schematic of the active lengthening of sarcomeres and the winding filament hypothesis is shown in Figure 2.2.1.

When addressing force generation during eccentric muscle actions, it is important to consider sarcomere inhomogeneity and the non-uniformity of individual sarcomere or half-sarcomere length changes. As sarcomeres increase in length, the opportunity for cross-bridge formation decreases and reduces active tension (Morgan and Allen, 1999). When sarcomeres extend beyond optimal length and operate on the descending limb of the length-tension curve, they become unstable and forcible lengthening occurs. The weakest sarcomeres extend beyond yield point and stretch independently of force, resulting in extreme and uncontrollable lengthening. This is referred to as sarcomere popping (Proske and Morgan, 2001). With continued and/or repeated lengthening, sarcomeres are thought to become overstretched in a hierarchical manner from the weakest to the strongest (Morgan, 1990). Operating on the descending limb of the length-tension relationship engages non cross-bridge structures, such as titin, to help maintain integrity of the sarcomere. Passive force increases with increasing length and is additive to the active forces generated, consequently enhancing overall force output (Figure 2.2.2). Upon relaxation some of the extended sarcomeres do not re-interdigitate and remain overextended. These structures can become damaged (Jones, 2004), resulting in disruption to sarcomere Z-line streaming and damaging the components underpinning the excitation-contraction coupling system (Proske and Morgan, 2001). This precipitates EIMD and affects muscle function. Although this could have implications for physical performance in an athletic context, it would result in a cascade of physiological responses triggering neuromuscular adaptation.

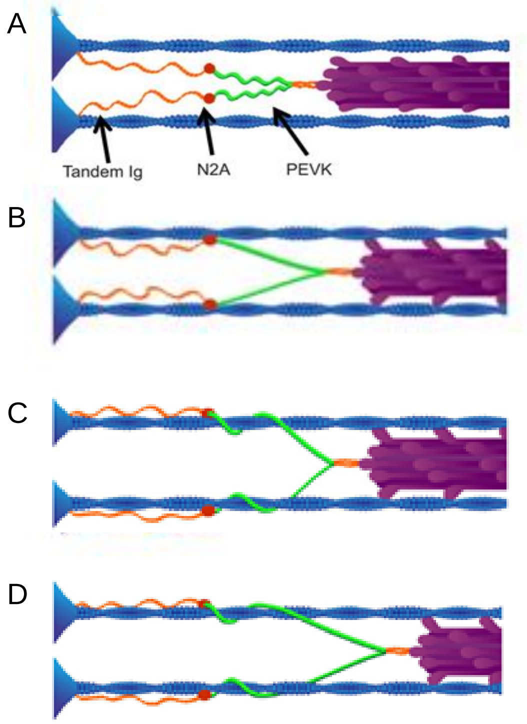

Figure 2.2.1. A schematic of the winding filament hypothesis. (A) Segments of titin attached to actin (blue) and myosin (purple) at resting length, (B) upon activation the N2A segment of titin binds to actin, (C) cross-bridge action wind the PEVK segment of titin, (D) the extension of the PEVK segment upon lengthening of the sarcomere whilst activated. Adapted from Nishikawa (2016).

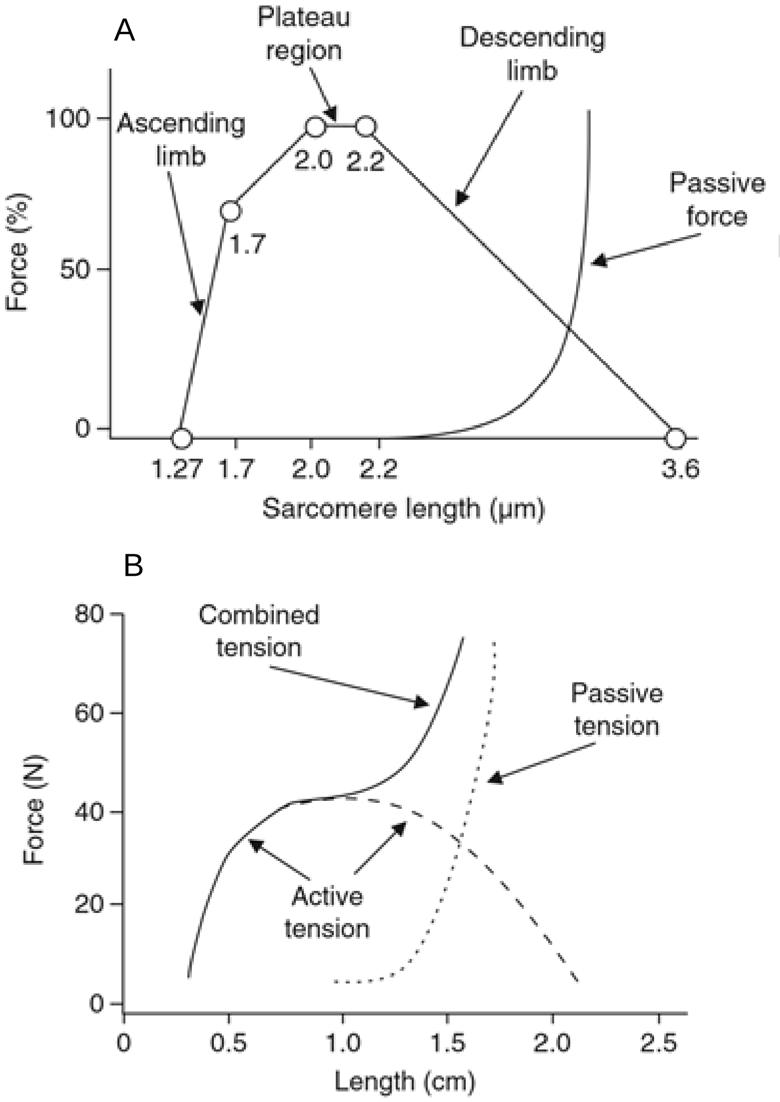

Figure 2.2.2. Schematic of a representative of the length-tension relationship of a (A) single fibre displaying the ascending, plateau and descending regions of the length-tension curve and the contribution of the passive force from lengthening of cross-bridges, and (B) whole muscle displaying the contributes of active and passive tension from lengthening of muscle (adapted from Brughelli and Cronin (2007)).

The unique features associated with eccentric muscle actions provides some explanation of the potential for greater force output compared to isometric and concentric muscle actions (Herzog, 2014). However, the basic physiological mechanisms underpinning muscle force production whilst lengthening are still a topic of debate (Herzog, 2018; Hoppeler and Herzog, 2014).

2.2.2 Neural Characteristics

The nervous system employs a different control strategy for activation during muscle lengthening action (Enoka, 1996a). This unique strategy contributes towards the greater force output observed during lengthening muscle actions. This notion is supported by evidence of reduced muscle activation (measured using electromyography, EMG) during lengthening versus shortening muscle action at a given force output (Bigland-Ritchie and Woods, 1976; Pasquet *et al*., 2006). Furthermore, there is evidence of incomplete muscle activation during eccentric muscle actions (Aagaard *et al*., 2000; Spurway *et al*., 2000). Whereas complete activation can be achieved during concentric and isometric muscle action. The activation shortfall has been attributed to pre-synaptic inhibitory mechanisms which contribute towards the disfacilitation of the motor neuron pool and post-synaptic mechanisms which reduce the responsiveness of the motor neuron pool (Duchateau and Enoka, 2016). Post-synaptic mechanisms encompass tension-regulation through the Golgi tendon organs, reciprocal and recurrent Renshaw inhibition (Aagaard, 2018). Although there is evidence of inhibition from post-synaptic origin (Barrué-Belou *et al*., 2016), these mechanisms are not seen as the main drivers of voluntary activation deficit but instead inhibition mediated by descending pathways from supraspinal centres (Duchateau and Enoka, 2016).

The inhibitory response and subsequent voluntary activation deficit when performing maximal eccentric effort is modifiable by strength training, whereby strength training can reduce or diminish the degree of inhibition (Aagaard, 2018). This is clearly demonstrated in the comparison of voluntary activation deficit evoked by electrical stimulus between untrained versus strength-trained athletes (Amiridis *et al*., 1996). Neural plasticity to strength training has been demonstrated previously, whereby training appears to alter corticospinal excitability and volitional drive and leading to enhanced eccentric strength (Aagaard *et al*., 2000; Tallent *et al*., 2017). This is indicative of decreased pre- and postsynaptic inhibition.

During submaximal and maximal effort eccentric muscle actions, the onset of cortical activation is earlier and greater brain area is involved versus concentric actions (Fang *et al*., 2001). Hence, the planning and preparation of this movement differs from that during shortening muscle actions. However recently, the relationship between motor unit recruitment and discharge rate has been identified as the main determinant of corticospinal output and not necessarily eccentric muscle actions, *per se* (Škarabot *et al*., 2018). The differences in motor unit recruitment (Nardone and Schieppati, 1988; Nardone *et al*., 1989) and altered discharge rates result in reduced muscle activation during eccentric versus concentric muscle actions (Pasquet *et al*., 2006).

Many researchers draw upon the study by Nardone and colleagues (Nardone and Schieppati, 1988; Nardone *et al*., 1989) as evidence of preferential recruitment of high threshold (i.e. fast-twitch) motor units and de-recruitment of low threshold slow-twitch motor units during eccentric muscle actions. However, these studies involved the assessment of the triceps surae during submaximal effort (15-20% of maximum voluntary contraction, MVC) eccentric muscle actions. According to a review conducted by Chalmers *et al.* (2008), this finding has not been substantiated despite numerous inquiries. Instead, it appears that the recruitment order of motor units is consistent with Henneman's size principle during submaximal (Pasquet *et al*., 2006; Stotz and Bawa, 2001) and maximal (Beltman *et al*., 2004) eccentric actions. Moreover, Beltman *et al.* (2004) evidenced recruitment of all fibre type populations during maximal effort lengthening exercise. However, despite observing preservation of the recruitment order of motor units in consistency with the size principle, other data from Pasquet *et al.* (2006) show that the activated motor units had lower discharge rates during eccentric muscle actions. Taken together, this information supports the notion that eccentric muscle actions have task-specific control strategies during lengthening and shortening muscle actions.

2.2.3 Metabolic Characteristics

Eccentric muscle actions require less energy for a given unit of force. Forceful detachment of cross-bridges does not require ATP splitting. This results in lengthening muscle actions being more economic in terms of energy expenditure versus an equivalent concentric muscle actions (Dufour *et al*., 2004; Perrey *et al*., 2001). An early study by Bigland-Ritchie and Woods (1976) clearly demonstrates the energy cost of positive muscle work is about six-fold greater than that of negative muscle work (Figure 2.2.3). The lesser degree of muscle activation for a given work rate signifies that there are fewer motor units being activated to produce the same output during eccentric versus concentric muscle actions. Consequently, for a given output there is less active muscle mass compared to when muscle is acting concentrically, thus is associated with a lower energy cost (Guilhem *et al*., 2013).

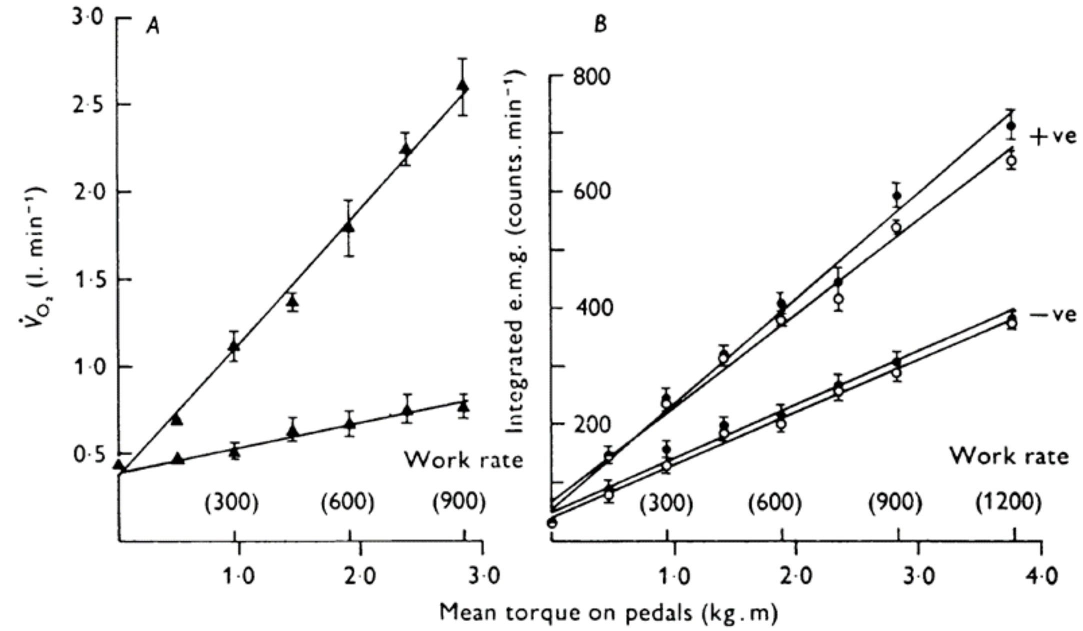

Figure 2.2.3. Seminal observations made by Bigland-Ritchie and Woods (1976) demonstrating the lower energy cost during lengthening muscle actions. Graphs shows: (A) mean rate of oxygen uptake, and (B) muscle activation measured using EMG plotted against mean torque during positive and negative work. Numbers in brackets represent work rate (kg·m/min).

To summarise, eccentric muscle actions are characterised by a combination of distinct mechanical, neural and metabolic features. This section has highlighted that when using eccentric muscle actions there is potential to perform a given submaximal force with metabolic and neural efficiency during negative (eccentric) work versus positive (concentric) work. Alternatively, there is potential to generate greater muscle force when increasing neural input. It is important to appreciate these qualities when applying eccentric exercise. The unique features mean that when training using eccentric muscle actions, performance capacity is unlikely to conform with guidelines pertaining to set-repetition-intensity training schemes that are commonly used to guide conventional resistance training prescription. Different approaches to training applications are required to optimise eccentric training regimes. Yet practitioners must be mindful that the relative simplicity of achieving very high muscle force output will increase the propensity of EIMD and the potential to cause detrimental effects on muscle function. Although disturbance to the neuromuscular system is required to stimulate adaptation, practitioners would need to consider applications that can be effectively managed within the sporting context to which they work. The purpose of this section was to address the overarching unique neural, mechanical and metabolic characteristics associated with lengthening muscle actions. This was to provide information to support the use of atypical resistance training applications that accentuate loading during eccentric muscle actions. The subsequent section will address the different methods of application that have been used to apply eccentric training for performance enhancement purposes.

2.3 The Role of Eccentric Muscle Actions in Athletic Endeavours

Athletes endeavour to achieve stronger and faster, and in some cases larger, muscle to execute forceful and rapid movements that are critical for success in their sport. Following habitual use of high-intensity eccentric exercise there is evidence of increased maximum force producing capacity during eccentric, concentric and isometric exertions (Coratella *et al*., 2015; Hortobágyi *et al*., 1996a). This response is likely to be underpinned by increased muscle activation (Higbie *et al*., 1996; Hortobágyi *et al*., 1996b) and muscle hypertrophy, predominantly of fast-twitch muscle fibres (Friedmann-Bette *et al*., 2010b). Adaptations in tendon and muscle passive stiffness following eccentric training is likely to facilitate the rapid transmission of muscle force to the skeletal system (Brumitt and Cuddeford, 2015; Lindstedt *et al*., 2001). Additionally, increased fascicle length (FL; Baroni *et al.,* 2013; Timmins *et al.,* 2016), which reflects the addition of sarcomeres in series within the myofibrils, is likely to influence muscle fibre shortening velocity (Franchi *et al*., 2017). Given that power is a product of force and velocity, adaptations arising from eccentric training are likely to have a strong positive influence on muscle power output (Aagaard, 2010). Power is a vital characteristic of many sports so the use of eccentric resistance training in athlete programmes is warranted. Especially for those athletes who are involved in strength-power sports where maximal strength and power output are key determinants of performance success.

Muscular strength is considered a major contributing factor to athletic performance (Stone *et al*., 2002). It is associated with improved force-time characteristics which translates to enhanced performance across a range of sports skills such as, throwing, jumping, sprinting and change of direction tasks (Suchomel *et al*., 2016). These skills involve rapid movement comprising a combination of coupled eccentric-concentric action (stretch-shortening cycle, SSC). During SSC action components of the muscle tendon unit act with spring-like function to rapidly decelerate and accelerate the body or body segments (Vogt and Hoppeler, 2014). Maximal strength, neural activation and muscle-tendon unit stiffness enables more effective absorption of forces during eccentric movement, more rapid transition to concentric movement to reutilise stored energy and an increase the overall efficiency of SSC performance (Komi and Gollhofer, 1997). On numerous occasions, high-intensity eccentric training has induced greater maximal muscle strength (Cadore *et al*., 2014; Colliander and Tesch, 1990; Coratella *et al*., 2015, 2018; Hortobágyi *et al*., 1996a, 1996b; Vikne *et al*., 2006) and improved SSC function (Komsis *et al*., 2014; Liu *et al*., 2013). Therefore, high-intensity eccentric exercise offers the potential to impact neuromuscular qualities that underpin aspects of SSC function which underpin an array of movements that comprise sports performance. Not only this, eccentric strength increases the potential for the muscle to withstand greater strain, thus offsetting the prospect of injury during sports play. High levels of eccentric strength in antagonist muscles provides protection against muscle strain injury during limb and body deceleration and can maintain integrity of joint structures when subject to high force (Aagaard, 2018).

Eccentric exercise also plays an important role in post-injury rehabilitation (LaStayo *et al*., 2013) by demonstrating efficacy in enhancing strength and muscle mass following anterior cruciate ligament surgery (Gerber *et al*., 2007a, 2007b). This type of injury is prevalent across many sports. Eccentric exercise has facilitated faster recovery to pre-injury muscle function and performance (Young *et al*., 2005), and maintenance of muscle mass and strength 12 months post-surgery (Gerber *et al*., 2009). Interestingly, unilateral eccentric exercise improves contralateral muscle strength (Farthing and Chilibeck, 2003a; Higbie *et al*., 1996; Hortobágyi *et al*., 1996b, 1997, 2000), which could offset the detrimental effects of immobilisation on muscle strength and function following injury or surgery.

Overall, training using eccentric muscle actions appear to lend towards the development of stronger, faster and larger muscle. This is likely to have a strong positive influence on muscle power output with the potential to improve performance during a range of movements that are involved in athletic activities. Additionally, the efficacy of eccentric exercise in injury prevention and rehabilitation provides further support for the use of eccentric training within an athlete's physical preparation regime.

2.4 Practical Application of Eccentric Exercise

2.4.1 Loading Considerations

As discussed previously, the unique features of eccentric muscle actions allow for much greater force to be produced during muscle lengthening versus shortening. However, traditional applications of exercise utilise the same absolute load for the descending (eccentric) and ascending (concentric) phase of an exercise, whereby load prescribed is limited to concentric performance. This approach to loading does not appropriately stimulate the eccentric force producing capacity of muscle as the descending portion of the lift is not loaded in relation to the individual's eccentric maximal force capacity. Instead, practitioners must apply alternative methods to prompt greater force output during the descending phase of exercise. This usually involves heavy external loads and demands a very high exercise intensity. There are a multitude of ways to apply and categorise eccentric exercise in research and practice. Usually, isotonic eccentric exercise intensity is prescribed as percentage of one repetition max (RM) during couple eccentric-concentric or concentric-only (CO) action, whereby the intensity of the load will either exceed, equal or be within the force producing capacity of the 1 RM. This is typically categorised as supramaximal, maximal or submaximal intensity, respectively.

It is common practice for S&C practitioners, rehabilitation professionals and sports science researchers to prescribe eccentric training loads (Barstow *et al*., 2003a; Ben-Sira *et al*., 1995; Brandenburg and Docherty, 2002; Douglas *et al*., 2018; English *et al*., 2014a; Friedmann-Bette *et al*., 2010b; Walker *et al*., 2016) and evaluate eccentric performance (Moir *et al*., 2013) grounded on RM strength tests. This approach to load prescription however, overlooks task-specificity and the possibility that some individuals have a different tolerance for eccentric exercise (Pickering and Kiely, 2017). For this reason, a number of researchers have adopted an eccentric specific RM assessment (Franchi *et al*., 2014, 2015; Gillies *et al*., 2006; Housh *et al*., 1998; Spurway *et al*., 2000; Vikne *et al*., 2006) in the endeavour to increase the efficacy of eccentric training regimes or enable the comparison of eccentric-only (EO) or CO using isotonic exercise.

Eccentric repetitions performed in isolation may have limited transfer to performance contexts due to omission of coupled eccentric-concentric action or the SSC, which is innate to a vast majority of athletic tasks (Wagle *et al*., 2017). To overcome this limitation, eccentric exercise can be performed as a coupled eccentric-concentric movement whereby the eccentric phase load is in excess of the concentric phase load. This approach to loading is termed accentuated eccentric loading (AEL). The inclusiveness of both phases of the exercise could be considered more appropriate when endeavouring a more rapid transfer of adaptations to performance of athletic tasks. The application of AEL can be used to acutely augment the concentric phase of a given exercise or as a means to offer more efficacious eccentric training stimulus.

Isotonic exercises are associated with strength curves which represent the variability in muscular force generated throughout a given range of movement (ROM) for a particular exercise. For a given load, there will be segments of the ROM where active force producing capacity is higher and the individual will have to actively lower the external load during the descending phase of the exercise. However, during the segments of the ROM where active force producing capacity is more restricted, the individual will have to shift their action from actively lowering the external load to resisting the downwards acceleration of the external load. The latter action will occur if the external load is sufficiently challenging an individual’s eccentric force producing capacity at a given ROM. Hence, the proficiency in the application of eccentric exercise using isotonic loading is highly sensitive to the choice of exercise intensity such that it sufficiently overloads the muscle at the required ROM. The required ROM is dependent on the characterisitics of the strength curve of the chosen exercise.

The application of isokinetic eccentric exercise differs from isotonic eccentric exercise, in that the computer-driven velocity control of an isokinetic device allows the user to exert maximum effort against the dynamometer across a given joint ROM (Guilhem *et al*., 2013). Throughout the ROM the intention is to resist the dynamometer lever arm whilst it overcomes the force exerted by the individual. This enables individuals to readily perform eccentric MVC (EMVC), concentric MVC (CMVC) or a target a percentage of MVC. Usually, eccentric exercise performed on an isokinetic device is an isolated muscle action and is usually used to compare against concentric or isometric actions (Higbie *et al*., 1996; Hortobágyi *et al*., 1996a, 1997; Seger and Thorstensson, 2005). However, this approach to performing eccentric exercise could limited transfer of training effects to performance contexts due to omission of the natural movement mechanics (Wagle *et al*., 2017). Maximal coupled eccentric-concentric actions can be performed on isokinetic devices which can addresses this limitation (Colliander and Tesch, 1990; Liu *et al*., 2013; Tesch *et al*., 1990). However, performing movement at a constant angular velocity is far removed from the demands imposed during typical human movement, which is an interplay of acceleration and deceleration. This could also act to limit the transfer of training effects to athletic tasks.

The overarching nature of eccentric exercise means that force generated by the muscle must be lower than that of the imposed force for the muscle to lengthen. However, the different characteristics innate to isokinetic and isotonic eccentric exercise could alter the neuromuscular control strategy (Duchateau and Enoka, 2016). Ultimately this could influence the nature subsequent neuromuscular and morphological adaptations between these two applications. This has been investigation on multiple occasions (Coratella *et al*., 2015; Doguet *et al*., 2016; Guilhem *et al*., 2010). In a review by Guilhem *et al.* (2010), when comparing the mean strength gains following eccentric training interventions using isokinetic versus isotonic paradigms, it appears that isotonic training increases the force producing capacity by 1.1 ± 1.0% per session across an average training duration of 8 ± 3 weeks versus isokinetic training which increases force producing capacity by 0.6 ± 3.0% across an average training duration of 11 ± 5 weeks. These data imply that isotonic loading may be a more efficient strategy for strength development. However, this cannot be certain as the differences in participant characteristics and prescription of key training variables are likely to play a major role in determining the nature and magnitude of outcomes.

2.4.2 Application of Load

Several applications have been used by S&C researchers and practitioners to employ eccentric training in laboratory and applied contexts. A vast majority of eccentric training interventions are conducted using isokinetic devices. This application omits the methodological difficulty associated with the manual application and withdrawal of load for the performance of high-intensity eccentric exercise during the descending phase of the exercise. However, the lack of specificity is exacerbated due to the tendency for devices to offer exercise which isolates joint actions. To overcome this limitation a small number of researchers have used custom-built isokinetic devices that facilitate multi-joint exercise, including; leg press and squat device (Komsis *et al*., 2014; Liu *et al*., 2013; Papadopoulos *et al*., 2014), upper and lower body cycle ergometer (Beaven *et al*., 2014; Elmer *et al*., 2013; Green *et al*., 2018) and step ergometer (Marcus *et al*., 2008).

Unfortunatley, the application of high-intensity eccentric training using multi-joint isotonic exercise in a performance environment is fraught with problems. Administering a sufficient stimulus in an efficient manner whilst considering the safety of athletes under extreme loads requires close supervision, assistance and/or specialist equipment. The type of technique employed by S&C practitioners is likely to be dictated by the magnitude of load requirements and whether the exercise is coupled eccentric-concentric or isolated movement. Commonly, manual assistance is provided by spotters to adjust the load between the eccentric and concentric phase of the exercise. Alternatively, spotters manually lift the load through the concentric phase to facilitate the performance of EO repetitions. However, this may not always provide the opportunity to safely maximise the load for the eccentric phase of a movement or allow for the efficient performance of coupled eccentric-concentric exercise. In this case, specialised equipment such as weight releasers are likely to offer a more stable and effective means to efficiently and more safely remove additional load.

Unfortunately, weight-releasers do not facilitate the performance of consecutive repetitions of AEL exercise as they must be reapplied following each repetition. This poses a logistical constraint in sessions with large coach to athlete ratios. To overcome this limitation custom-built machines have been developed to ease the application of high-intensity eccentric loads. These include; counterbalance weight systems (Barstow *et al.,* 2003; Kaminski *et al.,* 1998); electronic motor driven systems (English *et al*., 2014a; Franchi *et al*., 2014, 2015; Friedmann *et al*., 2004; Friedmann-Bette *et al*., 2010a; Yarrow *et al*., 2008); rig or pulley systems (Hollander *et al.,* 2007; Vikne *et al.,* 2006), hydraulic squat device (Frohm *et al.,* 2005), pneumatic smith machine (Douglas *et al*., 2018). Additionally, a host of devices have been developed for commercial use (see review by Tinwali *et al.*(2017)) and a variety of flywheel devices (Fernandez-Gonzalo *et al*., 2014; de Hoyo *et al*., 2016; Maroto-Izquierdo *et al*., 2017; Naczk *et al*., 2016; Suarez-Arrones *et al*., 2018; Tesch *et al*., 2004) to facilitate the application of eccentric exercise with greater control, efficiency and safety in an applied context.

Alternatively, there are techniques that practitioners can use to prompt AEL or a high-force eccentric training stimulus, which do not require specialist equipment or the manipulation of heavy external load. These techniques have the potential to be relatively self-sufficient. The two movements or the 2/1 technique uses a broader exercise to lift the load and a more restricted exercise to lower the load in odred to offer a more concentrated eccentric stimulus during the latter movement (Mike *et al*., 2015). Olympic lifting and derivative exercises, Nordic hamstring curls, plyometric exercises, depth jumps and loaded countermovement jump (CMJ) which consists of a handheld weight being dropped at the end of the eccentric phase and immediately prior to initiating the concentric action of the jump (Sheppard *et al*., 2008) will also facilitate the application of eccentric training stimulus. Generally, the complexity of the application of isotonic loading for eccentric exercise has led to a paucity of information in applied settings, especially compared to more traditional resistance training methods. This has limited the evidence about this activity, and importantly, the potential to understand the application for training prescription and adaptation.

2.5 Performance Responses

2.5.1 Isokinetic Exercise

A predominant finding in the literature is that training effects are specific to the muscle action used in training (Roig *et al*., 2009). Whereby, EO and CO training result in notably greater increases in eccentric and concentric strength, respectively. Specifically pertaining to EO training, following 6 weeks training at velocities exceeding 100º/s, quadriceps eccentric strength increased 20-30% whereas quadriceps concentric strength increased 1-4% (Duncan *et al*., 1989; Tomberlin *et al*., 1991). Increasing the training duration to 10 weeks regardless of training velocity appears to prompt greater increases in quadriceps eccentric strength ranging between 35-45%, with negligible benefit to concentric quadriceps strength which ranged between 4-7% (Higbie *et al*., 1996; Seger *et al*., 1998). The most drastic observation in the specificity of training effect was observed by Hortobágyi *et al.* (1996b) following 12 weeks of three sessions per week of EO training, a potent increases (116%) in quadriceps eccentric strength were observed in comparison to minimal improvements (5%) in quadriceps concentric strength. However, the magnitude of increase observed by Hortobágyi *et al.* (1996b) should be interpreted with caution, as a later study from this research group (Hortobágyi *et al*., 2001) documented a 22% increase in strength performance in seven days of consecutive training prescribing an eccentric exercise stimulus with an untrained, sedentary population. As a result, more active individuals may not display such a dramatic response to an eccentric training stimulus.

Despite reports of large discrepancies in improvements in eccentric and concentric strength to EO training regimes, a number of studies have demonstrated efficacy in increasing concentric strength to a greater degree when using an isokinetic approach to training and assessment (Blazevich *et al*., 2007; Cadore *et al*., 2014; Hawkins *et al*., 1999; Hortobágyi *et al*., 1996b; Miller *et al*., 2006). Hortobágyi *et al.* (1996a) observed a 13% and 42% increase in quadriceps CMVC and EMVC, respectively, following six weeks (four times per week, 24 sessions) of EO training (four sets of six to ten repetitions) at an intensity equivalent to CMVC through 60º/s, in a group of untrained sedentary females. Similarly, a study by Blazevich *et al.* (2007) documented a similar magnitude of improvements in concentric (16%) and eccentric (39%) strength following a longer training programme (ten weeks), but with lower training frequency (three times per week, 30 sessions) and greater training intensity (EMVC). The prescription of key training variables in this study offered a reduce volume (four to six sets of six repetitions) to account for the greater force requirement of each EO repetition and the longer time under tension (TUT) constraint (tempo: 30º/s). Although both studies approach the prescription of training slightly differently, it did not drastically affect the magnitude of the overall response.

Using a similar set-repetition scheme and training frequency as Blazevich *et al.* (2007), using a training tempo of 60º/s and extending the duration of training to 20 weeks (60 sessions), Miller *et al.* (2006) observed a similar improvement in quadriceps concentric strength (15%) but lesser magnitude of improvement in eccentric strength (28%). The extended programme duration did not offer additional benefit to quadriceps eccentric or concentric strength in a cohort of untrained females. Cadore *et al.* (2014) used a shorter training programme (six weeks) and lower training frequency (twice per week for 12 sessions) to attain a similar magnitude of strength improvements (15% and 30% increase in concentric and eccentric strength, respectively) in a cohort of inactive males and females. The prescribed programme was not too dissimilar to the programme offered by Blazevich *et al.* (2007); three to five sets of eight to 12 EO repetitions per set performed at EMVC through 60º/s. From these investigations it appears that completing a greater total number of sessions and longer training programmes does not confer notable benefit than the shorter duration programmes.

Interestingly, as a result of the 20 week training programme (three times per week, 60 sessions) prescribed by Miller *et al.* (2006), the strength response of the hamstring musculature was greater in magnitude (29% and 40% increase in concentric and eccentric strength, respectively) versus quadriceps strength response to the same programme. Notably, the magnitude of concentric strength improvement exceeded those of the other mentioned studies. Although a programme by Hawkins *et al.* (1999) does not support these findings. Using a similar programme duration and frequency (18 weeks, three times per week, 54 sessions) the response for the quadriceps exceeded that of the hamstrings for both concentric (18% vs. 13% respectively) and eccentric strength (22% vs. 14% respectively) and the magnitude of increase in strength was somewhat similar between modes of muscle action. The dissimilarity in findings of this study could be attributed to the different prescription of the exercise stimulus; three sets of three repetitions per session at EMVC through 60°/s is a lower training volume per session compared to the previously mentioned studies. This could explain the limited improvements seen in eccentric strength. However, the similarity in magnitude of improvement could be due to the within-subject design. Unilateral training whereby one leg is subjected to concentric training and the other, eccentric training could have resulted in cross-over of training effects to the contralateral limb (Farthing and Chilibeck, 2003b; Hortobágyi *et al*., 1997).

It appears that the upper body musculature responds in a similar manner to the lower body responses discussed previously. Nickols-Richardson *et al.* (2007) documented similar magnitude of increase in combined biceps and triceps eccentric (25%) and concentric (14%) strength compared to combined quadriceps and hamstrings eccentric (29%) concentric (15%) strength following 20 weeks (three sessions per week, 60 session) of one to five sets of six repetitions per set at EMVC through 60º/s. However, following a shorter programme (seven weeks) with increased session frequency (four times per week, 28 sessions), Komi & Buskirk (1972) observed a similar magnitude of increase (16%) in concentric and eccentric elbow flexor strength. Although the magnitude of improvement in concentric strength was comparable to those studies mentioned previously, the magnitude of improvement in eccentric strength could be underpinned by the distinctly lower training volume per session (one set of six repetitions at EMVC) compared to other studies.

The impact of EO training regimes on isometric strength has been demonstrated on numerous occasions (Coratella *et al*., 2015; Paddon-Jones *et al*., 2001; Pensini *et al*., 2002; Sharifnezhad *et al*., 2014). EO exercise has produced outcomes to a similar magnitude as isometric training (Pavone and Moffat, 1985). Some studies have found greater gains in isometric strength following EO versus CO training (Cadore *et al*., 2014; Hortobágyi *et al*., 1996a, 2000; LaStayo *et al*., 2000), whereas others have shown greater increase following CO versus EO training (Mayhew *et al*., 1995; Moore *et al*., 2012a). In some cases there has been similar increase in isometric strength following both modes of training (Blazevich *et al*., 2008; Komi and Buskirk, 1972; Pavone and Moffat, 1985) and no impact of

EO training on isometric strength despite showing improvements in both eccentric and concentric strength (Komsis *et al*., 2014).

A meta-analysis conducted by Roig *et al.* (2009) established that eccentric strength improvements induced by EO exercise tends to be specific to the velocity used in training. However, there is also evidence that strength improvements occurred at slower (Farthing and Chilibeck, 2003b; Paddon-Jones *et al*., 2001; Seger *et al*., 1998) and faster (Moore *et al*., 2012a) velocities than the joint angle velocity used in training. Shepstone *et al.* (2005) observed improvements in elbow flexor strength across a range of angular velocities (60-210º/s) following eccentric training performed slow (20º/s) and fast (210º/s).

The inclusion of coupled eccentric-concentric exercise when using isokinetic means is much less prevalent (Colliander and Tesch, 1990; Liu *et al*., 2013; Tesch *et al*., 1990). Specifically, Colliander and Tesch (1990) showed that this approach to training resulted in a concurrent increases eccentric (45%) and concentric (36%) strength following 12 weeks (three times per week, 36 sessions) of coupled eccentric-concentric movement using EMVC and CMVC in the respective phases through 60º/s. Additionally, strength improved at faster velocities than that used in training (90 and 150º/s) by 23% and 17%, respectively, for concentric strength, and ~31% for eccentric strength. Uniquely, alongside these observations this study documented a 25% increase in back squat 3 RM. This information provided a glimpse of how different aspects of strength can be simultaneously increased when training includes loading of both the eccentric and concentric phases of a movement. Furthermore, it implies that the training effects can be expressed during an alternate task which was not used for eccentric training. Importantly, isotonic assessment could be considered a more ecologically valid measure of strength in an S&C context. Notwithstanding, measurements of MVC provide valuable insight into the nature and magnitude of strength response following EO exercise.

Overall, training using isokinetic devices has enabled the implementation of exercise which stimulates greater force output during muscle lengthening. Of the isokinetic studies reviewed as part of this work, the exercise programme characteristics were mean ± SD; 9 ± 4 weeks in duration, 27 ± 12 sessions in total and includes 5 ± 2 sets of 9 ± 2 repetitions performed at an angular velocity of 80 ± 60º/s. The majority of these studies documented the efficacy of high-intensity eccentric exercise to increase eccentric, isometric and concentric strength predominantly in untrained or moderately trained populations. It is clear that the application of eccentric exercise using isokinetic devices provides a potent stimulus that is capable of prompting neuromuscular adaptation. However, it is difficult to apply the results to athletic populations. Furthermore, given the lack of practicality of this approach in an applied S&C context, it is necessary to consider applications that have been derived using isotonic means and to evaluate the efficacy of these applications for use by S&C practitioners.

2.5.2 Isotonic Exercise

A number of studies have demonstrated the efficacy of eccentric training using isotonic means for increasing maximum eccentric, isometric and/or concentric strength during isokinetic assessment (Coratella *et al*., 2015, 2018; Franchi *et al*., 2014, 2015; Kaminski *et al*., 1998; Pensini *et al*., 2002; Reeves *et al*., 2009; Spurway *et al*., 2000; Walker *et al*., 2016). However, the majority of investigations that have implemented isotonic methods have used strength assessments that are more relevant to a performance context, such as RM tests and vertical jump assessments (Cook *et al*., 2013; Coratella and Schena, 2016; Douglas *et al*., 2018; Friedmann-Bette *et al*., 2010a). Importantly, this enables a better understanding of how eccentric exercise can impact strength during tasks that are more closely related to movements required for resistance training and sports performance.

A review of the literature in this area revealed a number of studies that have utilised EO (Ben-Sira *et al*., 1995; Bogdanis *et al*., 2018; Cook *et al*., 2013; Coratella and Schena, 2016; Coratella *et al*., 2015, 2018; Dolezal *et al*., 2016; English *et al*., 2014b; Franchi *et al*., 2014, 2015; Reeves *et al*., 2009; Vikne *et al*., 2006; Yarrow *et al*., 2008) or AEL (Barstow *et al*., 2003b; Ben-Sira *et al*., 1995; Brandenburg and Docherty, 2002; Douglas *et al*., 2018; Friedmann-Bette *et al*., 2010a; Gillies *et al*., 2006; Kaminski *et al*., 1998; Sheppard *et al*., 2008; Walker *et al*., 2016) exercise. These studies show a great deal of variation in method of application, muscle group(s) trained, prescription of key training variables, training programme duration and training status of the participants. Coincidently, there is a greater prevalence of isotonic EO and AEL studies using strength-trained or athletic populations compared to the isokinetic interventions discussed previously. Given the appropriateness to the current work, attention will be direct towards these studies within this section.

Vikne *et al.* (2006) implemented EO or CO exercise with a group of track and field and powerlifting athletes using a custom built rig. Uniquely this study prescribed training intensity relative to eccentric 1 RM (ECC_{1RM} which was constrained to a tempo of three to four seconds) for the prescription of EO training load. The 12 weeks intervention offered 30 sessions in total and progressed training load from 8 RM to 4 RM (relative to CON_{1RM} or ECC_{1RM}) across the training period. A similar improvement in CON_{1RM} was observed between CO and EO groups (14% and 18% respectively). However, ECC_{1RM} improved to a greater magnitude for the EO (26%) versus CO (9%) group. Despite using an athlete cohort, the programme lacked practicality due to the exercise using isolated joint action, which is far removed from a practical context. Notwithstanding the administration of task-specific prescription of eccentric training load was tolerated and implemented successfully, which resulted in greater increase in eccentric elbow flexor strength.

Similarly Cook *et al.* (2013) implemented EO or traditional coupled eccentric-concentric (TRAD) exercise with a group of Rugby athletes. The researcher used manual assistance to lift the load through the concentric phase for the performance of EO repetitiones. Training load prescription was 120% $TRAD_{1RM}$ for the EO group and 80% $TRAD_{1RM}$ for the TRAD group. Both groups performed an array of upper and lower body exercises four times per week (two upper body and two lower body sessions) using four sets of five repetitions per exercise. The sessions formed part of a broader physical preparation programme. The intervention was six weeks in duration whereby over-speed running was prescribed for the final three weeks of the programme to facilitate the transfer of potential strength gains to running performance. The EO group increase bench press and squat 1 RM to a greater degree than the TRAD group. Following the transfer period, the EO group showed the greatest magnitude of lower body power improvement during vertical jump assessment. Sprint time (40 m) was augmented after the training transfer period for EO group but did not exceed the performance of the TRAD group. The authors concluded that there could be delayed training effects in the EO group that extended beyond the assessment period. Interestingly, although this study chose EO exercise which is limited in specificity to movements require in sports performance, the stimulus formed an S&C programme and therefore reflected the training regimes of an athlete. The study falls short in that the EO training was applied to several exercise and comprised a large training volume which could have reduced the effectiveness of the stimulus. Notwithstanding, it offers greater practicality than the study by Vikne *et al.* (2006).

Using much lower training volume per session, Friedmann-Bette *et al.* (2010a) observed performance improvements. The study implemented AEL or TRAD with 25 resistance trained, strength power athletes for six weeks for a total of 18 sessions using a seated knee extension computer driven device. The TRAD group trained using loads equivalent to 8 RM (six sets of eight repetitions), whereas the AEL group used an 8 RM load for the concentric phase but EMVC during the eccentric phase (five sets of eight repetitions). Repetitions were performed fast whereby each set was performed in 10-12 s. Both groups similarly increase 1 RM strength (16% and 19% for AEL and TRAD, respectively) and only the AEL group demonstrated an increase in squat jump (SJ) performance (7%). The TRAD group demonstrated minimal improvement (1%). Including AEL in this study appears to have proved more advantageous to jump performance versus TRAD. Interestingly, although this study has similar limitation that that of Vikne *et al.* (2006) due to the use of single joint action during training, the outcomes showed improvement in multi-joint function.

Walker *et al.* (2016) implemented AEL or TRAD with strength-trained males for ten weeks (two cycles of five weeks) using weight releasers on leg press and leg extension exercise. Participants performed two sessions per week of three sets of 6 RM and three sets of 10 RM for session 1 and 2, respectively. Repetition tempo was two seconds for each phase. Using concentric load plus 40%, the AEL group demonstrated a greater increase in isometric MVC (7%) versus the TRAD group (-1%) at week five and a prominent improvement at week ten (18% vs. 11% for AEL and TRAD, respectively). The AEL group increase EMVC at 30º/s (10%) but TRAD group did not. There were similar improvements in CMVC at 30º/s, work capacity and 1 RM performance following AEL (10%, 36% and 28% respectively) and TRAD (9%, 31% and 24%). The authors observed and increase in voluntary activation followed the AEL intervention only. The investigation incorporated isolated and multi-joint exercise using AEL, which extends upon that offered by Friedmann-Bette *et al.* (2010a). The inclusion of multi-joint exercise could explain the greater magnitude of increase in strength versus the TRAD group, which was not seen in the study by Friedmann-Bette *et al.*

As Friedmann-Bette *et al.* (2010a) was able to document an improvement in SJ performance following single-joint exercise, it would have been interesting to see whether the inclusion of multi-joint AEL exercise prescribed by Walker *et al.* would have facilitated jump performance to a greater extent. Vertical jump performance is commonly used among S&C practice to evaluate the efficacy of training regimes. Hence, the information would have held practical value. When specifically applying AEL to countermovement jump (CMJ) exercise, Sheppard *et al.* (2008) observed a small increase in maximum strength (4%) but much greater increase in vertical jump performance (11%), increased peak velocity (16%) and peak power (20%) in a group of volleyball athletes. The use of a jump as a training tool likely explains the greater improvement in jump performance versus maximum strength.

Fortunately, a study by Douglas *et al.* (2018) incorporates a combination of the aforementioned approaches to provide a wealth of information pertaining to the effects of AEL exercise on indices of strength, power, jump and sprint performance. Similar to the work of Cook *et al.* (2013), the study used a cohort of Rugby athletes who performed two cycles of four weeks (four sessions per week). The athletes performed slow AEL exercise for the first cycle and fast AEL exercise for the second cycle. The AEL stimulus was supplemented with plyometric exercise (drop and broad jumps). The outcome of this study revealed that slow AEL improved lower body strength and sprinting speed to a greater magnitude than slow TRAD, whereby the second cycle of fast AEL did not elicit further improvement to those attained using slow AEL. The investigation is ecologically valid, which is readily usable by practitioners. However, administration of multiple eccentric stimulus (through AEL back squat and plyometric exercise) and highly varied prescription of key training variable makes it difficult to draw firm conclusions about the efficacy of the AEL application.

The application of AEL for athletes and strength-trained individuals looks promising in terms of maximum strength and dynamic performance enhancement. The more ecologically valid means of application and assessment enables a better understanding of how eccentric exercise can impact strength during other tasks that are likely to be more closely related to movements required for resistance training and sports performance. In order to better understand the efficacy of eccentric exercise in athletic programmes it is first necessary to understand the fundamental prescription of key training variables (Moir *et al*., 2013). As a start, the isotonic exercise programmes that have been reviewed as part of this literature review show that on average (± SD) programmes span 8 ± 3 weeks in duration, included 19 ± 9 sessions in total of 4 ± 1 sets of 8 ± 5 repetitions per session, performed at an intensity of 55 ± 26% 1 RM for the concentric phase and 101 ± 28% 1 RM for the eccentric phase with a 3 ± 2 s tempo of the eccentric phase.

2.6 Mechanisms

Following habitual use of high-intensity eccentric exercise, researchers have observed an increase in maximum force producing capacity during eccentric, concentric and isometric maximum voluntary exertions (Coratella *et al*., 2015; Hortobágyi *et al*., 1996a). The adaptive response could have been underpinned by an increase in muscle activation (Higbie *et al*., 1996; Hortobágyi *et al*., 1996b), muscle hypertrophy predominantly of fast-twitch muscle fibres (Friedmann-Bette *et al*., 2010b) and an increase in fascicle length (FL; Baroni *et al.,* 2013; Timmins *et al.,* 2016). An increase in FL has the potential to positively influence muscle fibre shortening velocity (Franchi *et al*., 2017). This section will address these mechanisms in greater detail and in the context of the current literature.

2.6.1 Muscle Hypertrophy

The use heavier external loads to stimulate high muscle tension during eccentric muscle actions can cause disruption to the contractile and non-contractile elements of the muscle (Morgan and Allen, 1999). This phenomenon mediates an anabolic response that serves to strengthen the damaged tissue for protection against future damage (Nosaka and Aoki, 2011; Schoenfeld, 2012). Exercise that comprises of lengthening muscle actions has been found to stimulate muscle protein synthesis, increase intracellular anabolic signalling and upregulate gene expression (Schoenfeld, 2012). These responses are heightened following eccentric exercise compared to traditional loading approaches or shortening muscle actions (Franchi *et al*., 2014, 2015; Friedmann-Bette *et al*., 2010a; Moore *et al*., 2005). Although the efficacy of EO training (Bogdanis *et al*., 2018; Coratella and Schena, 2016; Coratella *et al*., 2015, 2018; English *et al*., 2014b; Farthing and Chilibeck, 2003b; Franke *et al*., 2014; Higbie *et al*., 1996; Hortobágyi *et al*., 1996a; Shepstone *et al*., 2005; Vikne *et al*., 2006) and AEL exercise (Douglas *et al*., 2018; Franchi *et al*., 2014, 2015; Friedmann-Bette *et al*., 2010a; Gillies *et al*., 2006; Walker *et al*., 2016) to increase indices of muscle hypertrophy has been documented on numerous occasions, it does not always result (Ben-Sira *et al*., 1995; Brandenburg and Docherty, 2002).

Using an athletic population, Friedmann-Bette *et al.* (2010a) demonstrated that six weeks of AEL exercise (concentric phase load was equivalent to 85% 1 RM, and eccentric phase load was approximately 1.9 times higher than concentric load) led to hypertrophy of predominantly of fast-twitch muscle fibres and induced a shift towards a faster muscle phenotype. These responses were associated with making a muscle better suited for fast, explosive movements. Similarly, Vikne *et al.* (2006) observed an increase in type II fibre CSA in well strength-trained athletes when using a more efficacious loading strategy during EO exercise. The importance of load as it relates to hypertrophic response was demonstrated following an eight week resistance training intervention by English *et al.* (2014b). The investigators implemented calf and leg press exercise of varying combinations of AEL load. Four groups exercised under four different conditions. Each group used the same load during the concentric phase of the exercise (which progressively increased throughout the duration of the study) and used eccentric loads corresponding to 33%, 66%, 100% or 138% of the prescribed concentric load. Each group completed two to five sets of two to eight repetitions (the combination of sets and repetitions had an inverse relationship throughout the programme). The results showed that the loading regime adopting 138% of CON_{1RM} increased measures of muscle hypertrophy to the greatest extent. Overall, it appears that utilising the higher force producing capacity may be crucial to the magnitude of hypertrophic adaptation.

Often the nature of investigations which address the hypertrophic responses to EO exercise does not replicate real training scenarios. Whilst these studies provide a reductionist approach, they are fraught with limitations and results in a lack of information that can be applied in the performance context. Those studies that have implemented AEL exercise have provided valuable information pertaining to the application of AEL as a means to induce hypertrophy in an applied context or with an athletic population. However, greater insight is needed to evaluate the efficacy of ecologically valid training applications in inducing muscle hypertrophy in well strength-trained individuals and athletes.

2.6.2 Muscle Architecture

The general consensus is that concentric exercise is more suited at increasing pennation angle (PA) and eccentric exercise is more suited to increase FL (Ema *et al*., 2016a; Franchi *et al*., 2014, 2015, 2017; Reeves *et al*., 2009; Timmins *et al*., 2016). Theoretically, this implies the addition of sarcomeres in series and parallel (Franchi *et al*., 2017), which have the potential to impact muscle fibre shortening velocity and force producing capacity, respectively (Narici, 1999; Reeves *et al*., 2009). These characteristics determine the efficiency of force transmission from muscle to tendon and therefore have a notable influence over muscle function (Ema *et al*., 2016a; Narici, 1999). The specific architectural remodelling response imply that the myogenic responses between the two muscle actions are different (Reeves *et al*., 2009). The activation of mitogen-activated protein kinase following eccentric exercise observed by Franchi *et al.* (2014) substantiates this notion.

The characteristic response to EO exercise performed using isokinetic means has been observed after four weeks of training; Baroni *et al.* (2013) detected an ~5% increase in FL in mid region the rectus femoris (RF) and vastus lateralis (VL). Continued training resulted in considerable increase in FL observed at week eight for both muscles (~15%) with the response tapering off at week 12 (~18%). Correspondingly, muscle thickness (MT) increased at weeks four and eight for both muscles (5-10%) but no further increase at week 12 was found. Over the training period PA did not increase above 4% from baseline values. Coratella *et al.* (2015) observed a similar response at the distal region of the VL; FL increased by 15% concomitant with an increase in MT (3%) and minimal change in PA (< 1%) following 6 weeks of EO exercise. Collectively, these findings imply that when exercising the quadriceps eccentrically at 60º/s for three to five sets of eight to ten repetitions per session for six to eight weeks (two sessions per week), this may be sufficient to induce considerable change in FL along the length of the VL Given that the exercise stimulus had minimal impact on PA, the increase in FL is likely to be the mechanism that underpinned the increase in MT for these studies in particular.

Not all studies demonstrate the typical characteristic response; Blazevich *et al.* (2007) observed a similar magnitude of increase in PA at the mid portion of the VL following EO (12%) and CO (11%) exercise, which exceeded the magnitude of increase in FL in both cases (3% and 6% for EO and CO, respectively) following five weeks of exercise. Interestingly, after a further five weeks of training FL did not show any further change for either training group. However, PA continued to increase in response to EO training (21%) but not in response to CO training (13%). There was an increase in MT following both modes of training (8-12%) which appears to be underpinned by changes in PA. The architectural response could be a representation of training at 30º/s, which is lower than the training velocity of the aforementioned studies. With the EO training programme implemented by Blazevich *et al.* (2007), adaptations in PA could take longer to manifest versus adaptations in PA induced by CO exercise.

When training and assessing the biceps femoris, Timmins *et al.* (2016) observed a different response to that mentioned previously. An inverse relationship between architectural adaptive responses was observed following six weeks of either EO or CO training at both fast and slow angular velocities (60º/s and 180º/s). Following EO exercise PA decreased by 7% and FL increased by 16%, whereas following CO exercise PA increased by 20% and FL decreased by 11%. Other studies have reported small decreases in measurements of PA in the biceps femoris following EO exercise (Guex *et al*., 2016; Potier *et al*., 2009). The characteristic response could be altered in this particular muscle or the hamstring muscle group. This could be due to innate differences in muscle architecture compared to the quadriceps musculature and fascicle kinetics during eccentric exercise, including magnitude of fascicle elongation during muscle lengthening.

At present it is unclear how movement velocity may impact the nature of the architectural adaptation (Ema *et al*., 2016a). Sharifnezhad *et al.* (2014) concluded that lengthening velocity was important for muscle longitudinal growth after observing an increase in FL (14%) in the mid portion of the VL following ten weeks of EO exercise performed at 240º/s, but not following three other EO exercise conditions imparting a training velocity of 90º/s. Other researchers have observed changes at slower velocities ranging from 30-60º/s. However, further investigation is needed into the differences in joint angle velocity on architectural adaptations to eccentric exercise regimes.

The studies that have been discussed previously have implemented the exercise interventions using isokinetic device. A small number of studies have captured architectural remodelling in response to EO (Franchi *et al*., 2014; Reeves *et al*., 2009) and AEL (Douglas *et al*., 2018; Seynnes *et al*., 2007) regimes when using isotonic approaches. The outcomes of studies implementing EO exercise were comparable to those derived from isokinetic studies in terms of the specific architectural remodelling response and concomitant increase in MT (Franchi *et al*., 2014; Reeves *et al*., 2009). However, the studies implementing AEL exercise demonstrated an altered response. Seynnes *et al.* (2007) found that the inclusion of a more efficaciously loaded eccentric phase coupled with a high-intensity concentric phase resulted in a simultaneous increase in architectural qualities that could be detected after three weeks. Overall, the five weeks training intervention resulted in a 10% and 8% increase in FL and PA, respectively, at the mid portion of the VL muscle. However, the findings of Douglas *et al.* (2018) demonstrated the inverse relationship in the response of the architectural characteristics but with conflicting findings between the response to fast and slow velocity AEL exercise. Slow AEL exercise resulted in FL increasing by 9% and PA decreasing by 3% at the mid portion of the VL. Whereas following fast AEL exercise there was a decrease in FL of 7% and an increase in PA of 5%. The AEL regime utilised a combination of maximal and supramaximal intensity isotonic exercise incorporated into the physical preparation programme of a group of Rugby athletes. Thus, the adaptive response may have been influenced by other training demands. Notwithstanding, these investigations have provided valuable information pertaining to the potential concurrent development of architectural characteristics (Seynnes *et al*., 2007) and the responses of trained individuals (Douglas *et al*., 2018). Both sets of information appear to be lacking in current research.

There are numerous reports of regional specificity of architectural adaptations to EO exercise (Franchi *et al*., 2014; Narici *et al*., 1989; Noorkõiv *et al*., 2014; Seynnes *et al*., 2007; Vikne *et al*., 2006). This adaptive response has been attributed to the serial heterogeneity of sarcomere lengths within muscle fibres (Huijing and Jaspers, 2005) and characteristics of the connective tissue matrix (Turrina *et al*., 2013). These factors affect the mechanical strains along a single muscle and influence the nature of lateral and longitudinal force transmission, causing variation in the intensity of the mechanical strain along a single muscle and the distribution of force among a muscle group (Turrina *et al*., 2013). Consequently, this would affect the nature of protein disruption and subsequent adaptation along a muscles length (Seynnes *et al*., 2007). Hence, different architectural response can occur along a single muscle. This substantiates the use of numerous measurement sites along a muscle when evaluating the effects of training on architectural response.

Naturally, muscle architectural arrangement differs between genders. It has been observed that males have greater PA and MT, whereas females have been shown to display longer FL (Kubo *et al*., 2003). The differences observed prior to invention could explain the differences in architectural adaptations of males and females to EO exercise. In a study by Coratella *et al.* (2018) a greater magnitude of increase in PA was associated with females versus males (14% and 5%, respectively), and a smaller magnitude of increase in FL was associated with females versus males (7% and 12%, respectively) following an eight weeks EO exercise intervention. Although the information from Coratella *et al.* (2018) does not directly relate to the difference in responses from trained versus untrained individuals, it demonstrates that different baseline architectural characteristics can affect the nature of the adaptive response. Hence, the differences in muscularity and architectural characteristics following resistance training (Ema *et al*., 2016b; Funato *et al*., 2000; Kawakami, 2005) suggests that trained individuals who have been exposed to long-term habitual resistance training would have different architectural characteristics versus untrained or moderately trained individuals. This would influence the nature of the architectural remodelling response as per the findings of Coratella *et al.* (2018). As mentioned, the architectural remodelling response in trained individuals is lacking therefore further investigation is needed to provide clarity of the effects of eccentric exercise on the force-velocity potential of an athlete's musculature.

2.6.3 Neural Function

The disproportionate increase in strength and morphological adaptation in response to high-intensity eccentric exercise highlights to prominent role that the neural system plays in the observed adaptive responses to exercise interventions (Brandenburg and Docherty, 2002; Hortobágyi *et al*., 1996a). This is further supported by the observations of contralateral effects of eccentric exercise improving strength in an immobilised or unexercised limb (Hortobágyi *et al*., 1997; Housh *et al*., 1998).

Following habitual eccentric exercise pre- and postsynaptic inhibition is suppressed or removed and a greater force output ensues (Aagaard *et al*., 2000). Facilitating force output, the neural responses to eccentric exercise comprises of increased H-reflex and V-wave responses (Tallent *et al*., 2017) inferring increased excitability of spinal motor neurons and elevated descending motor drive (Duclay and Martin, 2005). There have been numerous observations of increased agonist voluntary activation (Cadore *et al*., 2014; Higbie *et al*., 1996; Hortobágyi *et al*., 1996b; Liu *et al*., 2013; Pensini *et al*., 2002; Walker *et al*., 2016), decreased antagonist coactivation (Liu *et al*., 2013; Pensini *et al*., 2002) and alteration in synergist muscles EMG activity (Franke *et al*., 2014). Measures of EMG have been attributed to magnitude of activation of type II fibres, motor unit discharge rate and synchronisation (Higbie *et al*., 1996; Hortobágyi *et al*., 1996a). However, high-intensity eccentric exercise does not always induce measurable changes in muscle activation (Blazevich *et al*., 2008; Hortobágyi *et al*., 1996a).

Overall, the alterations in neural function in response to high-intensity eccentric exercise facilitate the expression of strength in agonist and synergist muscles, reducing the negative effects of antagonist coactivation. This can provide a platform for enhanced neuromuscular performance in athletic task and play an important role in injury prevention.

2.7 Exercise-Induced Muscle Damage

As mentioned previously, the unique neural control strategies (Enoka, 1996a) and distinct mechanical processes (Lieber, 2018) underpinning lengthening muscle actions offers the potential to generate very high muscle force. The metabolic cost is lower during eccentric muscle actions and therefore offers the potential to perform greater volumes of work at a given intensity versus concentric exercise. However, these features come at the potential cost of EIMD, which can be temporarily debilitating and will affect performance for several days. Symptoms of EIMD commonly emerge as reduction in neuromuscular function (Howatson *et al*., 2007; Souron *et al*., 2018), increased muscle stiffness (Jaskólski *et al*., 2007), muscle swelling (Chleboun *et al*., 1998; Yu *et al*., 2015), muscle soreness (Howatson *et al*., 2012) and elevated concentration of intramuscular protein in the blood (Howatson and van Someren, 2008). These symptoms can have an immediate and prolonged effect on muscle function (Byrne *et al*., 2004). From a performance perspective, an excessive and debilitating EIMD and fatigue response do not lend towards athletes who have competing training demands. An in-depth discussion of studies pertaining to the EIMD and fatigue response to high-intensity eccentric exercise is out of the scope of this work. However, an appreciation for the debilitative effects of eccentric exercise will assist in the development of appropriate prescription and evaluation of eccentric exercise and subsequent organisation of the training stimulus within the physical preparation programme of an athlete.

From a neural perspective, the loss of muscle function is underpinned by impaired action potential conduction velocity and transient changes in the central nervous system (Isner-Horobeti *et al*., 2013). From a mechanical perspective, the loss of muscle function is underpinned by compromised integrity of membranes of structures which are integral to the excitation-contraction coupling process, impaired calcium mechanics and increased passive tension and muscle stiffness (Hyldahl and Hubal, 2014). Connective tissue damage impedes the longitudinal transmission of force which contributes to strength loss. Local inflammation heightens the sensitivity type III and type IV nerve endings (Proske and Morgan, 2001), increasing perception of soreness with movement or palpation and can cause reduced joint ROM. Consequently, this can cause a significant detriment to an individual’s expression of force (Howatson *et al*., 2007). EIMD is indicated by an increase in circulating intramuscular cytosolic and structural proteins: creatine kinase, lactate dehydrogenase, myoglobin, troponin and myosin heavy chains (Hyldahl and Hubal, 2014). These markers and symptoms (force loss and muscle soreness) of muscle damage peak in the 12–72 hours following the exercise insult and usually recover within 10 days (Guilhem *et al*., 2013).

Although eccentric training offers a potent stimulus to increase muscle strength, power and hypertrophy, a common side-effect is EIMD and fatigue. Although damage is a precursor for muscle tissue regeneration and growth (Schoenfeld, 2012) and fatigue expected following training, excessive acute effects can be detrimental to performance. Therefore, it is vital that eccentric exercise is prescribed to athletes with sufficient intensity to offer sufficient disturbance to the neuromuscular system in order to prompt muscle tissue regeneration, growth and progression of neuromuscular function. However, it is also important that the response is not excessive such that physical performance in other task is severely diminished and training is negatively impacted to an excessive degree. The latter could lead to non-functional overreaching.

2.8 The Repeated Bout Effect

Following a single exposure to unaccustomed eccentric exercise it is usual to experience muscle pain and weakness which can last for several days. However, when the same or similar eccentric contractions are repeated, severe EIMD is prevented (Nosaka and Aoki, 2011). This can be attributed to neural, mechanical and cellular adaptations which attenuate the magnitude of EIMD. As mentioned in the previous section, EIMD comprises of symptomatic (e.g., force loss, muscle soreness), systematic (e.g., increased circulating muscle proteins), and histologic (e.g., myofibrillar disruptions) responses (Hyldahl *et al*., 2017; McHugh, 2003). The adaptive response is characterised by; changes in activation through increased synchronisation or recruitment of motor units which might better distribute the fibre stresses to limit myofibrillar damage, especially in type II fibres (Chen, 2003). Changes in passive and dynamic stiffness of non-contractile elements, such as desmin and titin, act to strengthen the structure of the sarcomere and increases in intramuscular connective tissue act to dissipate myofibrillar shear stresses (McHugh, 2003). The number of sarcomeres in series increases to reduce sarcomere strain and mechanical disruption during lengthening action (Morgan, 1990). Serial compliance shifts the length-tension relationship towards longer muscle lengths, which is a remodelling response to confer protection when exposed to future muscle lengthening particularly at longer muscle lengths (Proske and Morgan, 2001). The adaptive response following exposure to a single exercise insult can provide a protective effect which can last for six to nine months (Nosaka and Aoki, 2011; Nosaka *et al*., 2001, 2002). This adaptation is referred to as the *repeated bout effect*. With this phenomenon, the repeated exercise is likely to result in a similar decrement of force loss and impaired performance immediately post exercise, but the effects of the repeated bout are evident in the recovery period in the hours and days following exposure to the exercise.

It has been shown that a low volume bout of eccentric exercise is sufficient to attenuate the detrimental effects of EIMD to a similar degree as a higher volume of eccentric exercise (Howatson *et al*., 2007). This is useful information when first exposing athletes to novel eccentric training stimulus. The prescription of low volume exercise, akin to that prescribed in the study by Howatson *et al.* (2007), is a more accurate reflection of how high-intensity eccentric exercise might be prescribed in a performance context. The majority of muscle damage studies have prescribed excessive intensities and volumes to intentionally cause EIMD and fatigue, such as the high volume bout prescribed by Howatson *et al*. (2007). Hence, the prescription parameters used in studies of this nature would not be suitable to translate to the performance context. Notwithstanding, muscle damage studies are valuable to enhance our understanding of the acute responses which are likely to underpin some of the chronic adaptations observed with longer-term eccentric training interventions. From a practical perspective, it is important to acknowledge the characteristics of the acute adaptive response. For example, if a markedly attenuated adaptive response is observed following the repeated bout then practitioners may need to adapt the exercise bout or increase session frequency to ensure that the exercise stimulus is sufficient enough to continue to prompt muscle tissue regeneration and growth.

2.9 Conclusion & Implications for Coaches

Eccentric muscle actions appear to play an important role in the physical preparation of athletes and the use of eccentric exercise to enhance muscle morphology and neuromuscular function appears promising. The adaptations arising from eccentric training are likely to have a strong positive influence on muscle power output (Aagaard, 2010). This warrants the use of eccentric resistance training in athletic programmes, especially those who are involved in strength-power sports where maximal strength and power output are key determinants of performance success. The paucity of information pertaining to the application of high-intensity eccentric exercise in a performance context has limited the potential to understand the application for training prescription and adaptation. Therefore, the overarching aim of this thesis was to better understand the application of novel high-intensity eccentric exercise in a performance context. The intention was to contribute towards the body of knowledge pertaining to eccentric training science, whilst assisting S&C coaches with the use of eccentric exercise in their practice. Specifically, this work comprised of seven experimental chapters which correspond the following seven aims:

1) To gain an insight into what S&C practitioners know and use in regard to eccentric resistance training for the high-performance athlete
2) To evaluate the function and use of a bespoke leg press device designed for strength training and research
3) To evaluate the efficacy of isometric strength assessment performed on a leg press device
4) To evaluate the mechanical response to high-intensity eccentric exercise and understand how it alters with changing conditions
5) To gain an insight into the immediate exercise-induced alteration in muscle function and muscle ultrastructure following an initial and repeated bout of high-intensity eccentric resistance exercise.
6) To determine the repeatability and specificity of eccentric force output and assess the methodological accuracy when using non-specific measures of strength to prescribe eccentric training loads
7) To ascertain the feasibility of a strength training programme which incorporates a progressive, task-specific approach to eccentric load prescription.

Chapter 3

An Exploratory Research Questionnaire: The Practices Employed by High-Performance S&C Practitioners when Using Eccentric Exercise

3.1 Introduction

The efficacy of eccentric training to enhance neuromuscular function has been discussed in detail in the previous chapter (Chapter 2). Naturally, conducting a comprehensive review of the literature has highlighted limitations of existing eccentric training research. An overarching limitation was that the majority of inquiries have used populations or processes that are limited in the transfer to athletic populations and contexts. Intuitively, this provides an overarching direction for forthcoming research. However, in order to be impactful to practice it is vital that the sub-sections of this work address the specific needs and performance questions offered by S&C practitioners. Hence, it seemed apt to conduct a practical review of eccentric training practice to attain a more complete review of the topic area, such that an appropriate series of investigations could be developed for this thesis. Therefore, this investigation addressed the first aim this thesis, which was to gain an insight into what S&C practitioners know and use in regard to eccentric resistance training for the high-performance athlete.

This information was used to explore the lines of scientific inquiry pertaining to eccentric training that would be most valuable to high-performance S&C practitioners and which had the potential to inform their practice.

3.2 Methods

3.2.1 Experimental Overview

An electronic questionnaire was distributed to a cohort of high-performance S&C practitioners which took approximately 10-15 minutes to complete. The survey was designed to explore S&C coaches' experiential knowledge and insights of eccentric resistance exercise and highlight performance questions that have originated from high-performance contexts.

3.2.2 Participants

Participants were recruited through a high-performance sport network as these individuals would provide information-rich responses relevant to elite athletes. Those participants were encouraged to pass on details of the investigation to other high-performance practitioners working within and/or outside of the UK. This method of recruitment is referred to as 'chain sampling' which is a nonprobability sampling technique used as a means to capitalise on expertise (Suri, 2011). The inclusion criteria were that respondents are currently, or had previously, specialised in the S&C professions and are working or have worked with elite athletes at National, International and/or Olympic level. Prior to completing the questionnaire, participants provided informed consent. All methods were approved by Northumbria University Research Ethics committee.

3.2.3 Procedures

The questionnaire comprised of a combination of closed and open-ended questions. Open-ended questions were included to gather richer explanations without inducing bias from the investigator or limiting the information that the practitioners could provide (Smith and Caddick, 2012). The questions offered space for the respondents to provide details about the methods they have used to employ eccentric exercise with athletes, to describe their experiences and to express their perspectives about the usefulness of eccentric exercise for the physical preparation of athletes. Additionally, the format of these questions ensured that the respondents could suggest areas that they would like to see investigated. These aspects may have been missed if using solely closed ended questions. Overall, five open-ended questions were included in the questionnaire which addressed; observations, limitations or concerns and noteworthy remarks about the application eccentric training regimes. These were followed by questions addressing research areas of interest and any other comments and thoughts about the use of eccentric training within an athlete's physical preparation programmes.

The remaining questions were closed-ended questions in multiple choice format. These questions addressed practitioner demographics and the background of sports and athletes that they have worked with. Next, the questions addressed the programmes that practitioners have used to employ eccentric exercise (i.e. methods and equipment used, set-repetition schemes, training loads). A subsequent section addressed how (and if) practitioners have used a variety of different methods of eccentric exercise and whether they feel that there is benefit in using these methods. Prior to distributing the questionnaire, a pilot questionnaire was distributed to four practitioners to assess its suitability for the intended audience. The questionnaire was distributed using an online survey tool (Bristol Online Surveys, Bristol, UK).

3.2.4 Data Analysis

Responses were extracted from the online survey tool. Analysis procedures included frequency counts and percentage calculations of closed-ended question and Likert-type scale responses. Open-ended question responses (qualitative) were coded with NVivo software (QSR NVivo 11). Thematic analysis for qualitative responses established emerging themes (Patton, 2002; Sparkes and Smith, 2013), which were then grouped into lower and higher order themes (Nowell *et al*., 2017). Themes were refined through repeated reviews of raw responses (Côté *et al*., 1993). To enhance trustworthiness of the results, analyst triangulation was used whereby a second researcher analysed a sample of the responses, independently, to establish agreement between researchers (Nowell *et al*., 2017).

3.3 Results

Characteristics of Respondents. There were 100 respondents who met the inclusion criteria, 95% were male and 5% female. The mean ($\bar{x}$) ± standard deviation (SD) age was 34 ± 8 years and the average duration working within the S&C discipline was 11 ± 8 years. Current job roles included: S&C Coach (56%), Senior S&C Coach (31%), Academic (7%), High-performance Director (4%), S&C Consultant and Academic (1%), Sports Scientist (1%). These roles were part of a sports institute (41%), professional sports club (31%), higher education or collegiate system (15%), private sector (7%), consultancy (5%) or a National Governing Body (3%). Current roles have been held for 4 ± 4 years. Collectively, the respondents reported 124 cases of working with Olympic level athletes, 105 cases of working with International level athletes and 84 cases of working with National level athletes across a broad range of sports. The average time spent with a single sport was 4 ± 3 years. The S&C specific qualification held by the respondents included accreditation provided by S&C professional bodies: UK Strength and Conditioning Association, Australian Strength and Conditioning Association or National Strength and Conditioning Association (67%), MSc (16%), BSc (5%), PhD (2%), Weightlifting (2%) or none (8%).

Application of Eccentric Training Methods. The majority of respondents reported that they have prescribed AEL exercise in programmes ranging from endurance to strength-power athletes (75%). A summary of the how practitioners use (or would like to use) a variety of eccentric resistance training methods is shown in Figure 3.3.1.

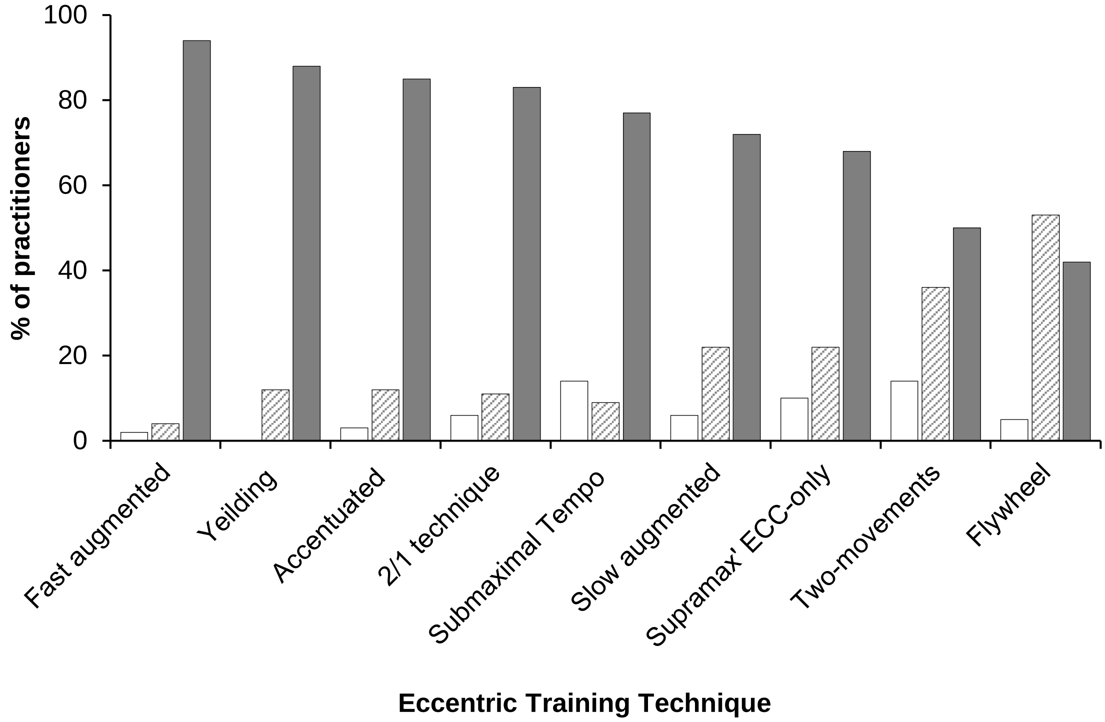

Figure 3.3.1. The use of different eccentric training techniques. White bars denote the response; *'never used and not inclined to use'*, striped bars denote the response *'never used, but willing to use'* and dark grey bars denote the response *'have used'*. For a full description of techniques, see Appendix 2: Eccentric Training Techniques.

The reasons underpinning non-use of the methods shown in Figure 3.3.1 were: equipment access (57%), not fully knowledgeable of training method (39%), inappropriate athlete population (36%), unconvinced about the value of the method (29%), supervision issues due to large athlete training groups (23%), high injury risk (11%), caused excessive muscle soreness (11%), lack of scientific evidence supporting its use (7%), the stimulus is not a priority for the required adaptations (3%), concerns of overtraining (2%), disapproval from coaches and/or medical staff (2%) or the application is overcomplicated (1%). Respondents reported that they had used a variety of equipment to employ eccentric training with their athletes (Figure 3.3.2) to target a variety of adaptations (Figure 3.3.3).

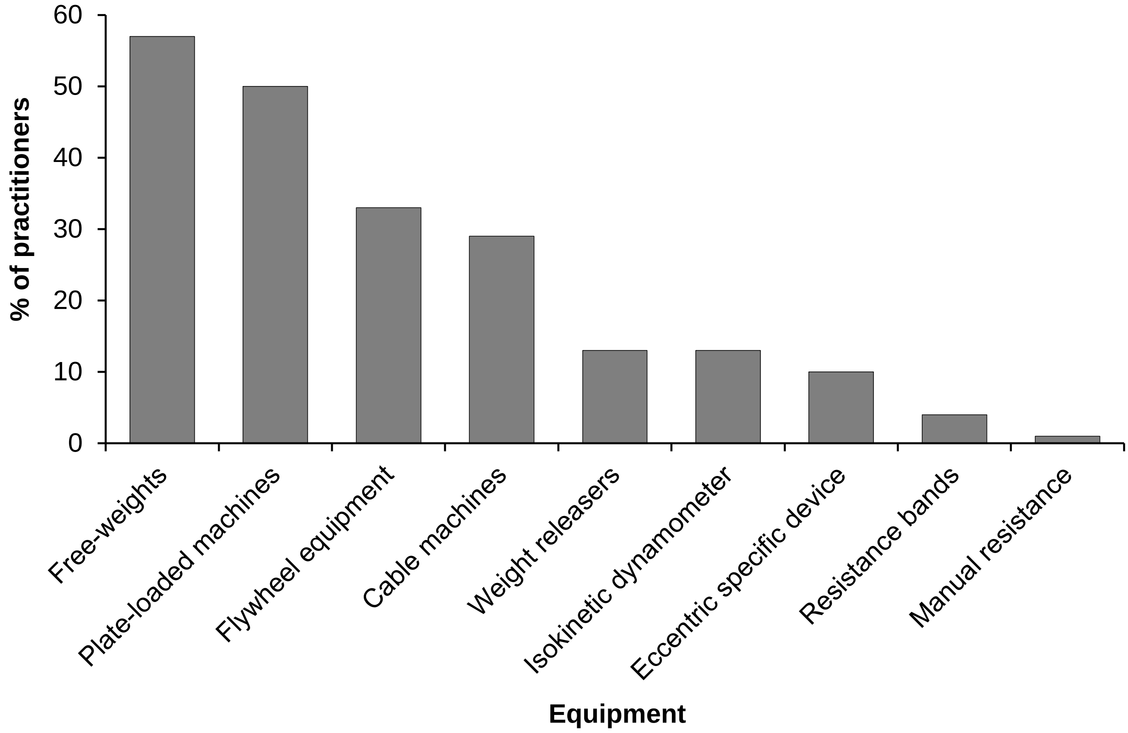

Figure 3.3.2. Equipment used to employ eccentric training with athletes.

Collectively, practitioners provided 160 examples of eccentric training regimes that have been used with their athletes. Programmes were categorised based on the repetition range that was used: < 6 repetitions (*n* = 110) and > 6 repetitions (*n* = 50) which is commonly used to distinguish between strength and hypertrophy programmes. Exercise selection and prescription of key training variables are summarised in Figure 3.3.4. The source(s) of information that practitioners have used and currently use to inspire their eccentric training programme content include: scientific journals (61%), S&C colleagues (58%); influential practitioners (52%), personal experiences (52%), professionals or academics (40%), the Internet (24%), books (20%) and certification or courses (8%).

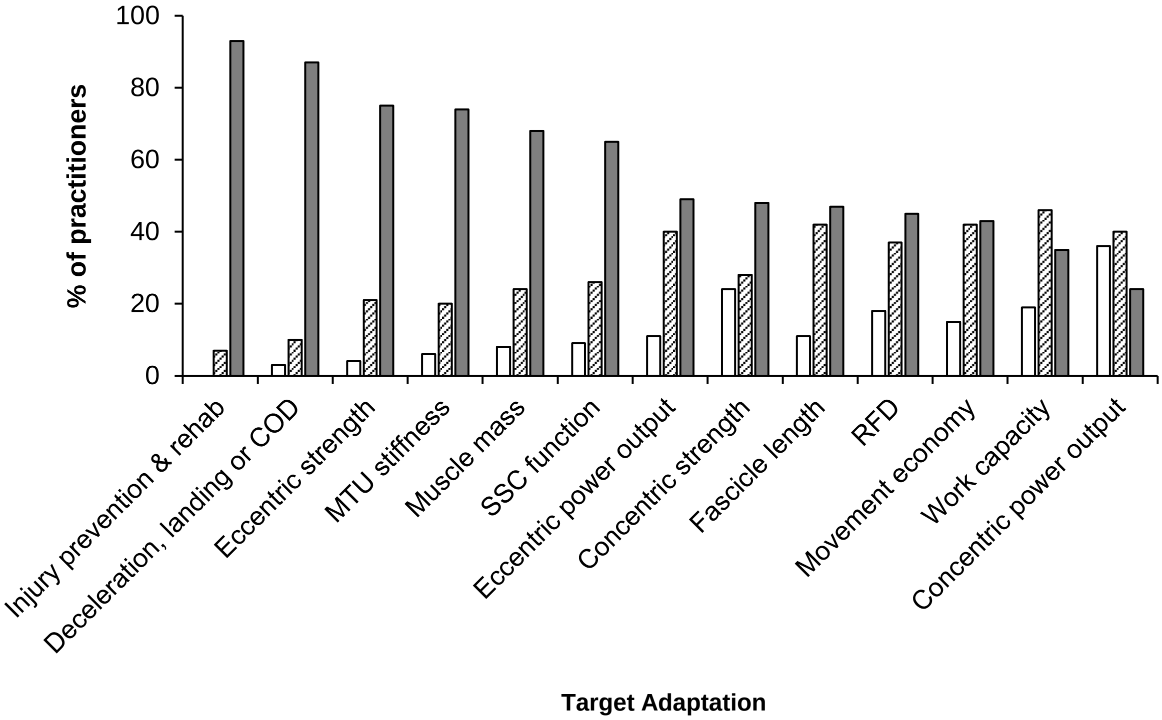

Figure 3.3.3. Target adaptations when using eccentric training with athletes. The response address whether practitioners *would not* (white bars), *would* (striped bars) and *have* (grey bars) use(d) eccentric training to target the said adaptation.

Perceptions of and Experiences when Using Eccentric Training. The majority of practitioners (84-98%) considered supramaximal and submaximal eccentric training as an *above average* to *extremely effective* training tool to prevent injuries, enhance muscle size and structure, increase mechanical function and enhance sports specific performance. A large portion of practitioners (62-75%) considered supramaximal and submaximal eccentric training *above average* to *extremely important* to athletes who do not have a predominant eccentric specific action or skill in their sport. The majority of practitioners considered themselves between *above average* to *extremely knowledgeable* about the underpinning science (89%) and training methods (90%) relating to supramaximal and submaximal eccentric training. The majority of practitioners rated themselves as *above average* to *extremely confident* to use submaximal eccentric training with their athletes (93%), but fewer practitioners rated themselves as *above average* to *extremely confident* to use supramaximal eccentric training with their athletes (68%).

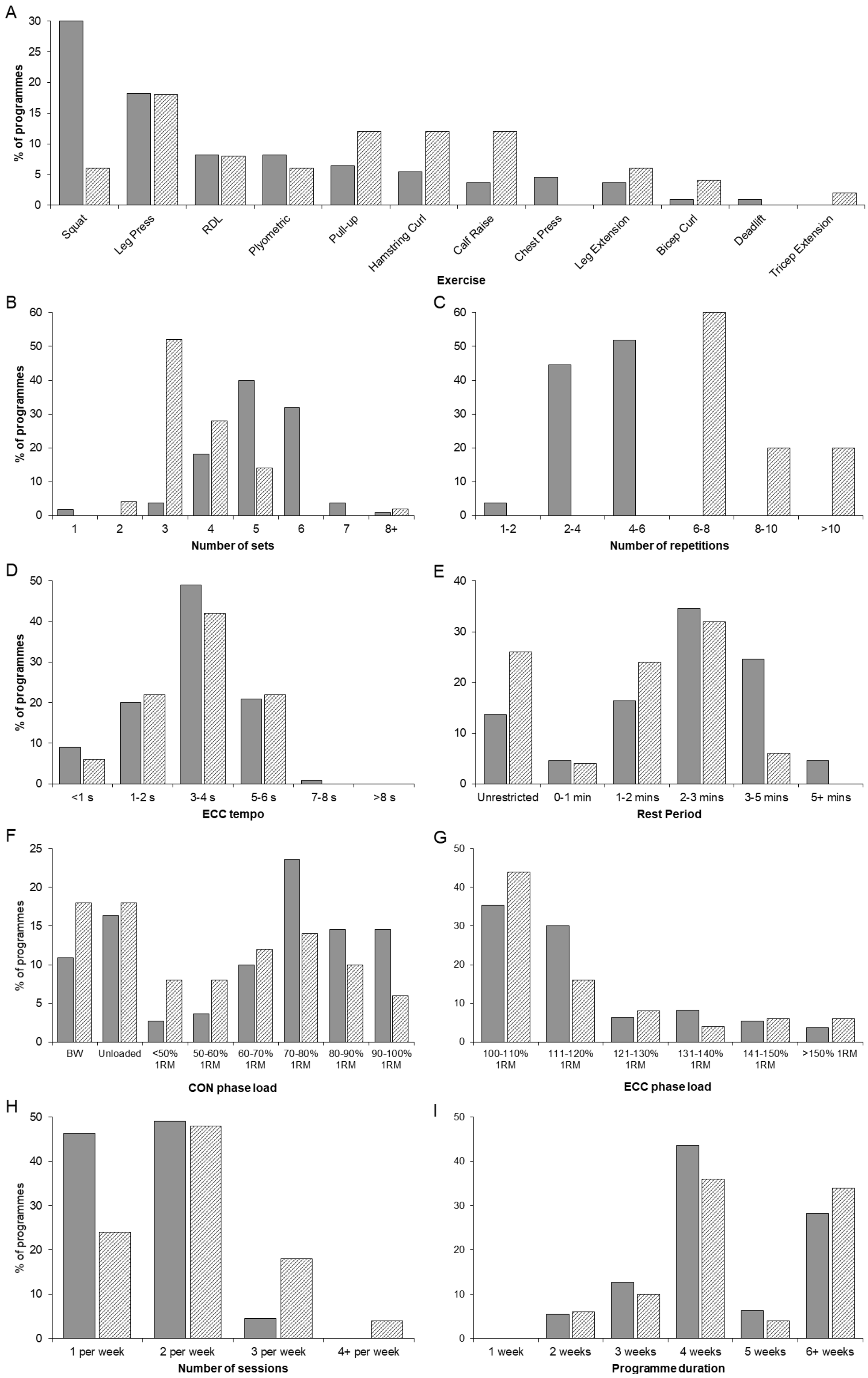

Figure 3.3.4. A summary of exercise selection and prescription of key training variables of 110 sample programmes. Programmes that used < 6 repetitions are denoted by dark solid grey bars and > 6 repetitions are denoted by light grey striped bars. % 1RM is relative to traditional 1 RM for graphs F and G.

Key themes emerged from the data that were gathered using open-ended questions. Data were grouped into two dimensions; (1) current thoughts and views about eccentric with athletes and, (2) experiences when using eccentric training with athletes (Figure 3.3.5 and Figure 3.3.6). Collectively, underpinning these two dimensions were 40 nodes creating lower order themes grouped into six higher order themes. Importantly, finding generalisations across the responses enabled the investigator to summarise information derived from a somewhat large sub-group of the target population so that the inferences drawn from these generalisations intend to resonate with the broader target population (Smith and Caddick, 2012). Consequently, scientific research that addresses these queries should hold relevance to the applicable setting, which can be used to inform practice (Polit and Beck, 2010). More specifically, to ensure validity of this qualitative information, criteria based on the 'non-foundational approach' offered by Smith and Caddick (2012) were used as a framework. The framework addressed the clarity of a response and coherence of a group of responses to offer consistency within a given theme which make sense when taken together and when displayed to the reader through direct quotations underpinning the given theme.

In reference to Figure 3.3.5, generally practitioners reported positive neuromuscular adaptations and minimal detrimental effects on other aspects of performance. However, the major barriers associated with the practical application of eccentric exercise was the impracticality of applying eccentric loads:

> *Primarily, equipment causes the biggest barriers. In particular, the ability to supramaximally load the eccentric portion of the lift safely and with user-friendly ease and stability. (P57 – Senior S&C coach)*

When eccentric regimes were applied, prevalent athlete and coach perceptions were acute muscle soreness:

> *Athletes felt very uncomfortable with the programme due to the amount of muscle soreness [the athletes] experienced. (P25 – Senior S&C coach)*

However, practitioners expressed the relatively rapid dissipation of muscle soreness in subsequent sessions:

[The athletes] got used to it over the first few weeks of the programme so [muscle soreness] became less of an issue. (P13 – S&C coach)

Additionally, prevalent athlete and coach perception included the substantial demand that high-intensity eccentric exercise places on the athlete during training;

Athletes need to be very mentally engaged, and exercises are both physically and mentally fatiguing. Exercises were not performed as desired if the athlete was tired/fatigued or not mentally engaged. (P39 – S&C coach)

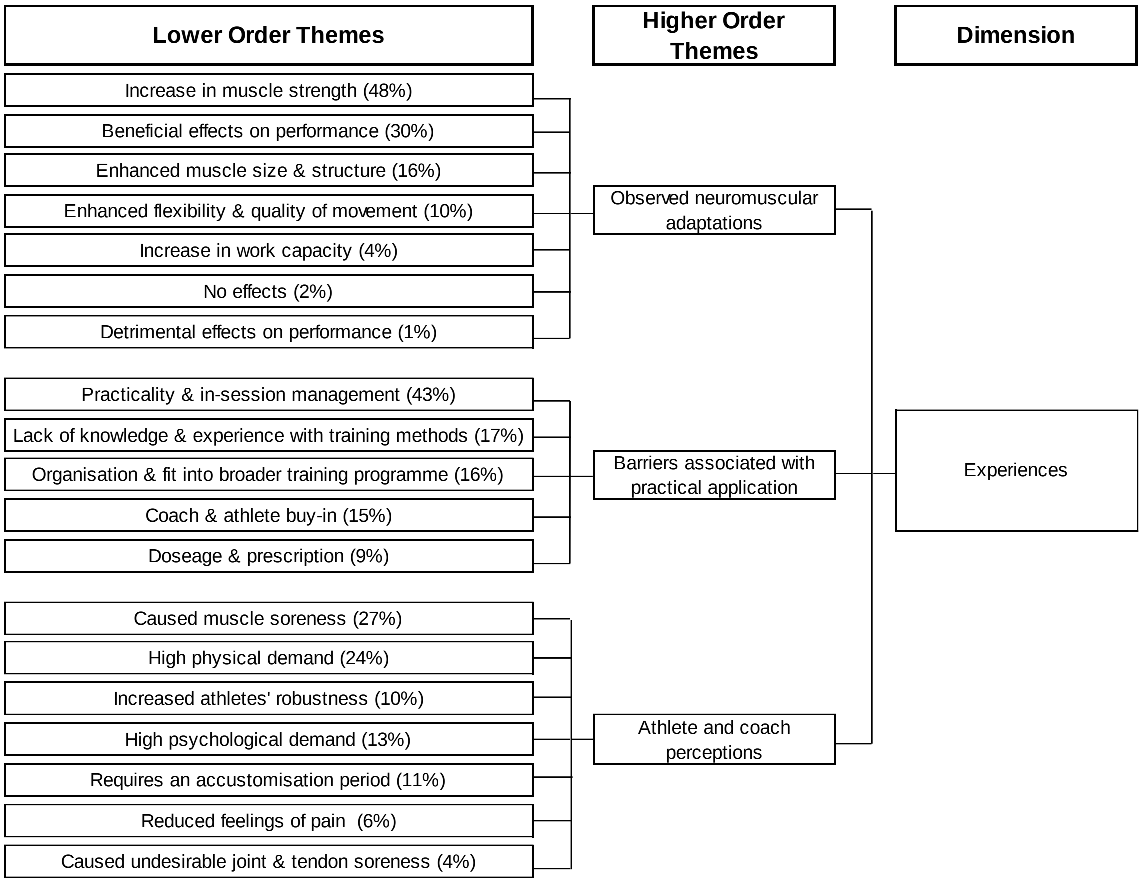

Figure 3.3.5. Experiences when implementing eccentric training in an athletes training regime. (Percentage of respondents in brackets).

In reference to Figure 3.3.6, a prevalent concern among practitioners is the debilitating effects of muscle soreness and fatigue, and the higher injury risk and safety concerns that is associated with high-intensity eccentric exercise:

[A concern is] fatigue from eccentric protocols, especially with sprint running athletes, and risk of injury and the safety with general lifting equipment with regards to loading supramaximal eccentric and failing (P40 – Lead S&C coach)

[Heavy loads] offers the potential for increased connective tissue injury and spinal stress and injury (P95 - S&C coach).

In order to promote evidence-based practice practitioners would like to see practically relevant scientific enquiry:

[I would like to see] more practice-based evidence from the high-performance environment rather than from journals using non-elite athlete. (P35 – Senior S&C coach)

Additionally, the athletes overall physical and psychological preparedness limits the use very high-intensity eccentric exercise in a performance context:

I have been unwilling to try with 'normal' key lift gym exercises (e.g., squats and deadlifts, etc.) – I think this is because of the technical and psychological limitations the individual may have. (P24 – S&C coach)

Many athletes are not 'strong enough' to need eccentric overload training. (P12 – S&C coach)

Practitioners suggested that more learning opportunities and sharing of knowledge would serve to improve their eccentric training practice:

[I would like to have] discussions with coaches who have used eccentric training extensively for a number of reasons. To understand rationales and how that dictated the details within programmes and subsequent outcomes. (P45 – S&C coach)

Practitioners offered a variety of performance questions that they would like to see investigated as part of future scientific inquiry, with prevalence towards; the transfer of benefits to sports performance, dose-response effects of different forms of eccentric training regimes, specifically addressing neural, morphological and structural adaptations to regimes and addressing different methods of implementation.

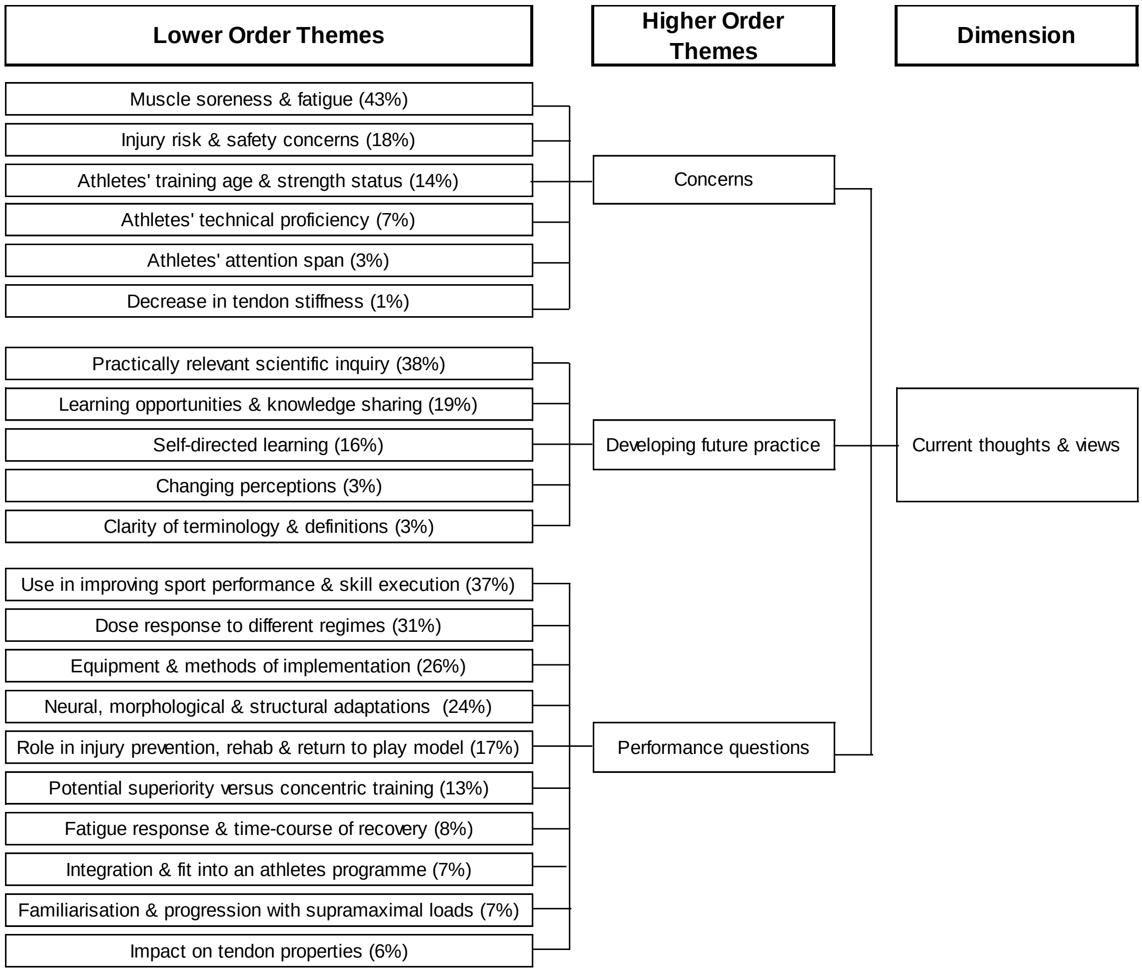

Figure 3.3.6. Current thoughts and views about using eccentric training in an athlete's training programmes. (Percentage of respondents in brackets).

3.4 Discussion

The aim of this investigation was to gain an insight into what S&C practitioners know and use in regard to eccentric resistance training for the high-performance athlete. These data show that the most prevalent performance questions that were suggested by practitioners related to the dose-response effects to different eccentric training regimes in terms of neuromuscular and morphological adaptations and, importantly, performance of sports specific skills (Figure 3.3.6). Queries related to various means and methods of applying eccentric training, which were generally associated with the requirement for safe and manageable approaches when using eccentric exercise in an S&C context (Figure 3.3.5 and Figure 3.3.6). A main concern was the detrimental effects of excessive muscle soreness and fatigue (Figure 3.3.6). Overall, there was an appeal to see more practically relevant scientific investigations conducted with the high-performance environment and elite athletes in mind.

Previously, a number of studies have collated information from S&C practitioners and sport coaches as a means to explore knowledge and better understand practices within a specific context. These include; exploring the practical knowledge of expert S&C coaches (Dorgo, 2009), determining the influence of scientific research on S&C practice (Durell *et al*., 2003), exploring coaches philosophies about the transfer of strength training to sports performance (Burnie *et al*., 2017) and describing the S&C practices of athletes, i.e. strongman competitors (Winwood *et al*., 2011) and distance runners (Blagrove *et al*., 2017). A number of these studies have been conducted as a means to inform and develop educational programmes (Dorgo, 2009). Some have been used to identify new ideas that can be used to improve training practice (Winwood *et al*., 2011). Whereas others provide insights to enhance understanding for the purpose of conducting applied research (Burnie *et al*., 2017). Whilst this investigation was implemented for a similar purpose, the uniqueness of the approach was the focus on eccentric exercise. A topic that, to the author's knowledge, has not been addressed previously in a qualitative manner. Particularly with the experiential knowledge of 100 high-performance S&C coaches who held on average 10 years' experience within the profession. The responses have provided valuable information of the gaps in the current knowledge and practice regarding eccentric training practice within the S&C profession working with high-performance athletes.

The respondents reported using scientific journals as their main source for eccentric training information. The majority of peer reviewed journal articles that have conducted eccentric training investigations have used untrained or moderately trained populations and have employed single-joint exercise using isokinetic means (Douglas *et al*., 2017). Athletes are physically well-conditioned and unlikely to respond in the same manner as untrained individuals (Ahtiainen *et al*., 2003). Furthermore, sporting movements tend to require multi-joint coordination and therefore training using multi-joint exercise is likely to optimise the transfer of gains to sports performance (Young, 2006). Hence, the applicability of the outcomes of a vast majority of eccentric training studies to a performance context is limited and reflects the respondents' requests for more practically relevant scientific inquiry (Figure 3.3.6).

A few studies have recognised and addressed the aforementioned limitations (Bogdanis *et al*., 2018; Coratella and Schena, 2016; Walker *et al*., 2016), but present the eccentric stimulus in isolation. Although it is extremely beneficial to understand the effects of an eccentric stimulus, it is equally important to understand the effects when it is incorporated into a broader physical preparation programme. Some investigators have successfully employed eccentric stimuli within athletes training programmes using methods and means that S&C coaches could reproduce (Cook *et al*., 2013; Dolezal *et al*., 2016; Douglas *et al*., 2018; Sheppard and Young, 2010). These studies are vastly different in terms of overall programme content, eccentric stimulus, loading parameters, performance markers, total programme duration and athlete characteristics, which is likely to have a large impact on the nature of adaptations. This impedes firm conclusions being drawn about the potential effects of ecologically valid eccentric training regimes. Notwithstanding, these studies have provided valuable information about a range of adaptive responses which includes the effects on some sports specific key performance indicators (i.e. sprint and jump performance), in response to eccentric training placed within an athlete's broader physical preparation programme. However, more investigations that appreciate a performance context are needed to support these findings and continue to broaden our understanding of the adaptive response to different eccentric training regimes for athlete performance enhancement purposes.

This investigation has highlighted that a major concern is the detrimental effects of excessive muscle soreness and fatigue, and the subsequent potential increase in injury risk as a result of this. When the basic principles of training are appropriately considered and they are integrated logically into a training process, adaptation is optimised and fatigue is appropriately managed (DeWeese *et al*., 2015a). This reduces the likelihood of overtraining and maladaptation to increase the potential for improved performance. The programming and prescription of eccentric training regimes is therefore central to the aforementioned concern. Exercise prescription and programme design for eccentric exercise has been studied far less when compared to conventional exercise. Training interventions used in scientific investigations rarely feature periodised training programmes.

There are some resources are available that propose prescription parameters for eccentric training sessions (Cowell *et al*., 2012; Mike *et al*., 2015; Tobin, 2014) but do not address the effects of such regimes. As a result of inquiry, two eccentric loading themes emerged in the present study (Figure 3.3.4). One theme included squat or leg press exercise performed for 5-6 sets of 2-6 repetitions with 70% 1 RM load during the concentric phase and 100-120% 1 RM load during the eccentric phase performed at a tempo 3-4 seconds, with 2-5 mins of rest between sets. This regime was performed 1-2 times per week for 4 or 6 weeks. Another theme included leg press, RDL, leg extension, hamstring curl or pull-up exercise performed for 3 sets of 6-8 repetitions with a load equivalent to bodyweight or unloaded during the concentric phase and 100-110% 1 RM during the eccentric phase performed at a tempo of 3-4 seconds with more than 2 minutes rest between sets. This regime was performed 2 times per week for 4 or 6 weeks. These data provide some insight into how eccentric training is currently prescribed by practitioners. But generally, there is a lack of evidence-based prescription of key training variables and clear programming guidelines that offer gradual accumulation of work along with manageable variation and the incorporation of planned recovery periods to aid physical and psychological recovery, especially when compared to conventional modes of training (DeWeese *et al*., 2015b).

When theming the responses, muscle soreness and fatigue were frequently used simultaneously when expressing concerns about implementing high-intensity eccentric resistance training with athletes (Figure 3.3.6). Although they differ on a physiological level, they were not separated in the analysis as it was not always clear whether respondents were referring to central or peripheral mechanisms resulting in reduced muscle function being their primary concern. It is important to emphasis that some disruption to the muscle tissue and nervous system function is necessary to stimulate central and peripheral adaptations. Although the respondents express muscle soreness and fatigue as a concern, it would appear appropriate to suggest that concerns were likely pertaining to unnecessary, excessive and/or detrimental muscle damage, soreness and fatigue leading to non-functional overreaching. Therefore, S&C practitioners could benefit from information pertaining to optimal loading regimes, particularly relating to the minimal effective dose of high-intensity eccentric stimuli. This could assist in productively incorporating the high-intensity stimulus into physical preparation programmes. From this, levels of fatigue and soreness can be managed, as in normal practice, using monitoring (McGuigan, 2017) and recovery strategies (Howatson and van Someren, 2008).

The respondents queries related to various means and methods of applying eccentric training and were generally associated with the requirement for safe and manageable approaches when using these in an applied context (Figure 3.3.6). The results from the quantitative part of this study show that a variety of techniques have been employed (Figure 3.3.1), generally using free-weights and plate loaded machines (Figure 3.3.2) and predominantly for squat and leg press exercise (Figure 3.3.4A) to target a wide variety of adaptations (Figure 3.3.3). The specific use is likely to be determined by the nature of the athlete’s sport. The type of technique employed is likely to be dictated by the magnitude of load the practitioners want to prescribe in their athletes’ programmes and whether the movement is coupled eccentric-concentric or EO movement. Manual assistance can be provided by athletes or practitioners to adjust the load between the eccentric and concentric phase of the exercise, but this may not always provide the opportunity to maximise the load for the eccentric phase of a movement safely and efficiently. For squat exercise in particular, weight releasers (Walker *et al*., 2016) are likely to offer a more stable means to remove the additional load. The use of a leg press machine could reduce spinal compression that squat exercise is likely to impose, but similarly, the adjustment of load or the performance of eccentric-only repetitions will pose a significant logistical and safety constraint.

To overcome this limitation the use of a relatively self-sufficient eccentric method such as the 2-1 or two-movements method (Mike *et al*., 2015) would suffice. However, during the 2-1 method the use of very heavy loads during single limb movement might cause misalignment of the spine and shoulder girdle or pelvis position for upper or lower limb exercise, respectively, heightening risk of injury. Specific eccentric devices or custom built machines have aided the application of heavy eccentric loads bilaterally (Douglas *et al*., 2018; English *et al*., 2014a; Frohm *et al*., 2005; Yarrow *et al*., 2008). Overall, squat and leg press exercise are the most common exercises used to employ eccentric exercise. With safety and practicality in mind leg press exercise will offer less spinal compression when subjecting athletes to heavy eccentric loads, where specific devices or custom-built machines are likely to be the most efficient and versatile option for the application eccentric stimulus during coupled eccentric-concentric or eccentric-only exercise. That said, as equipment access was highlighted as a barrier to practical application then investment into more self-sufficient methods such as those suggested by Mike *et al.* (2015) is also warranted.

A barrier associated with the practical application of eccentric training was a perceived lack of knowledge and experience with some eccentric training methods (Figure 3.3.5). A main reason for not implementing certain regimes because practitioners perceived themselves to be not fully knowledgeable of the training method. These outcomes likely underpin the results that show that approximately one third of practitioners rated their confidence as below average when using supramaximal eccentric training with their athletes. The respondents suggested that learning opportunities and knowledge sharing would serve to develop their future practice (Figure 3.3.6). Presumably, the increase in knowledge would foster their confidence to implement eccentric training regimes with their athletes. Interestingly, the source(s) of information that the respondents least use to inform their eccentric training programme content is certification and courses (8%), which suggests that there may be a lack of education through formal certification or professional development activities pertaining to eccentric resistance training. Therefore, it would seem pertinent to suggest that professionals (scientists and applied practitioners) who are experienced in using eccentric training should integrate their knowledge to develop informal and formal education opportunities. Overall, this would support the professional development of S&C practitioners by upskilling their competencies pertaining to eccentric training practice and enabling them to effectively utilise eccentric training methods with their athletes.

Eccentric resistance exercise is a broad reaching term that can cover many areas. The lack of absolute specificity to a certain area meant that the exploratory research questionnaire obtained a number of brief responses. This could have been attributed to the wording, interpretation or ordering of the questions. Approaching the exploration using interviews could have attained more insightful information across a number of the questions, through the use of prompts and cues. Using this approach, information could emerge that would help to provide with greater structure and insight to a particular area. In the context of where this research was conducted, there was a number of S&C practitioners within the English Institute of Sport that would have been available to interview. Future research that is conducted with the or similar organisations should consider to pros and cons of each approach with questionnaires having the potential for a large number of responses, but questionnaire have the potential to obtain greater quality information. Notwithstanding, there were several questions and lines of enquiry that arose from this investigation, however the overarching theme was a request to see more practically relevant research investigations that has applicability to elite athletes and conducted with high-performance environment in mind. Abiding to this theme and addressing the neuromuscular and morphological responses to eccentric training regimes, methods for the safe application of load and/or regimes that show consideration for the magnitude of soreness and fatigue are likely to assist S&C practice when using eccentric resistance training for the high-performance athlete.

3.5 Applied Perspective

The aim of this investigation was to gain an insight into what S&C practitioners know and use in regard to eccentric resistance training for the high-performance athlete. This specifically addresses the first aim of this thesis. To the author's knowledge, this investigation was the first to summarise eccentric training practice in a cohort of high-performance S&C practitioners. Importantly, this investigation served to supplement the literature review by conducting a practical review to gain a more complete evaluation of the topic area. In doing this, a wealth of information was gathered that was used to shape the present work and ensure that it would be impactful to S&C practice. Although it was not feasible to address all issues and performance questions put forward by the respondents, several queries have been considered. The subsequent chapters will address; the application of eccentric exercise using a leg press device for a safe and efficient means of performing high-intensity eccentric exercise (Chapter 4 and 6), the immediate training-induced effects of high-intensity eccentric exercise to assist with the development of appropriate eccentric training stimulus (Chapter 7) and the neuromuscular and morphological responses of strength-trained individuals to an eccentric training stimulus placed within a broader S&C programme and the application of this regime with professional athletes (Chapter 9).

Chapter 4

The Feasibility of a Custom-Built leg Press Device for Use in Research and Training

4.1 Introduction

As highlighted in the previous chapter, the application of multi-joint, high-intensity eccentric exercise in a performance environment is fraught with problems. Administering a sufficient stimulus in an efficient manner whilst considering the safety of athletes under extreme loads requires close supervision, assistance, and/or specialist equipment. These limitations have led to a paucity of information in applied settings, especially compared to more traditional resistance training methods. This has limited the evidence about this activity, and importantly, the potential to understand the application for training prescription and adaptation.

In addition to this, to determine the effectiveness of eccentric strength training programmes S&C practitioners must have a means to quantify and ascertain progression (DeWeese *et al*., 2015a; Sheppard *et al*., 2011). Isometric multi-joint tests are a common method of assessing maximal force capacity and ARE be used to assess progression of strength. This has been done using squat (Bazyler *et al*., 2015) and mid-thigh pull (De Witt *et al*., 2018) exercises. However, the anatomical position required to perform these tests can compromise the trunk and spinal column due to high levels of compression, thus increasing the potential for injury.

The development of an inclined leg press device provides a solution to the difficulties posed by high-intensity eccentric and isometric training and testing. The machine enables efficient application of very high loads eccentrically and can easily be adjusted to an isometric device to facilitate strength evaluation. Generally, leg press exercise requires minimal technical proficiency, avoids compression of the spinal column and is supportive of the trunk, yet still requires multi-joint co-ordination of the lower limb which is likely to optimise the transfer of gains to sports performance (Young, 2006). Therefore, this investigation aimed to evaluate the function and use of a bespoke leg press device designed for strength training and research. This specifically addresses the second aim of this thesis.

4.2 Methods

4.2.1 Device Design

By default, the 45° incline leg press device acts as a traditional leg press device, but modifications allow it to be converted to an isometric or eccentric device (Sportesse, Somerset, UK, Figure 4.2.1). The eccentric function of the leg press operates via a pneumatic system. The system has the potential to offer an additional 280 kg of load which is applied by pneumatic technology during the descending phase of the leg pressing movement. This load is automatically ‘unloaded’ at the predetermined end position which corresponds with the end ROM of the exercise. The ‘unload’ is achieved with adjustable magnetically operated switches (reed switches) situated on the machine’s framework. These switches trigger the application and withdrawal of the imposed resistance when the foot carriage passes each switch. This reduces the load at the end of the descending phase allowing the user to return the carriage back to the start position under concentric conditions unassisted. A dial controls the air pressure which dictates the applied resistance. The dial, which is operated manually, can move freely with marked lines corresponding to different magnitudes of load. The isometric function of the leg press operates via an inbuilt locking mechanism that can secure the carriage at any position along the machine's framework. When operating as a conventional device, external load can be added using weight plates that can be stacked above the foot carriage. Exercise on the device elicits some hip but predominantly knee flexion and extension against a constant load, thus targeting the muscle groups of the lower body.

The leg press foot carriage comprises of two smaller, independent carriages that connect with a removable steel bar. In total, weighing approximately 90 kg. However, instrumentation was added which increased this load. The total system load will be clarified as a part of this investigation. Each force plate consists of two parallel steel plates with four s-type load cells (300 kg limit per cell) which were mounted between each plate in each corner. The four load cells fed into a combinator to create a single voltage output. Associated with each force plate was a potentiometer (Hybritron®, 3541H-1-102-L, Bourns, Mexico). The load cells and potentiometers acquire data at 200 Hz. The voltages from the loads cells and potentiometer was relayed to data acquisition software (LabVIEW 6.1 with NI-DAQ 6.9.2, National Instruments Corporation, USA) onto a desktop PC. Force-time data for each force plate (left and right carriage) and displacement-time and velocity-time data for each potentiometer (left and right carriage) were displayed using the software. Raw data was exported from the data acquisition software into Excel format (Microsoft Office, 2010) and were analysed offline.

4.2.2 Device Calibration

Without instrumentation the foot carriage load was ~90 kg, therefore the total load of the foot carriage was determined to account for the additional load of the instrumentation. The dial to control pneumatic resistance had seven markings corresponding to load increments of 40 kg. The increments were too large for training and testing, therefore the dial was marked with more increments and verified. To do this a steel box was mounted onto the seat of the leg press device and positioned to align evenly with the surface of the force plates. The foot carriage was lowered to the box ensuring the surfaces were contacting evenly. In this position, a reading of force was taken with the pneumatic resistance control dial at 0 (carriage weight only) and then at 0.5 increments up to the maximum of 7 (14 pneumatic loading conditions - seven incremental load values were provided by the manufacturer and seven values were intermediate theoretical values derived from those provided by the manufacturer). The investigator was vigilant with accurately aligning the dial with the marked lines across all loading conditions and repeated measurements (Figure 4.2.1A). This process was repeated four times in total, but with varying order of resistance between 0 and 7. Measurements of these parameters were taken at four separate time-points to determine repeatability. An average of the four measurements were taken for each incremental load which were then evaluated against manufacturer's standards.

Figure 4.2.1. The custom-built leg press device. (A) Pneumatic resistance control dial and (B) air compression unit for loading during the eccentric phase, (C) rack for stacking weight plates for loading which will apply to the concentric phase, (D) removable steel bar insert for uni/bilateral function, (E) dual force plates, (F) safety mechanisms: carriage lock and release switch and adjustable height safety pins, (G) adjustable seat, (H) adjustable magnetically operated switches for loading/unload of pneumatic resistance, (I) series of latches along the frame work for securing the foot carriage for isometric testing, (J) T-bar pull switches to adjust the function to an isometric device.

4.2.3 Device Function

The machine was sampled under conventional, eccentric and isometric conditions to highlight any potential methodological issues with the function of the device that needed consideration prior to devising and conducting investigations. This was conducting with a sample n = 1, as the intention was to gain a preliminary insight into the devices function and to explore the potential differences in mechanical stimulus offered when using the device in its different modes. Identifying the differences in mechanical characteristic behaviour between conventional and eccentric exercise would provide preliminary information about the potential of eccentric exercise performed on the device, which proved useful when devising the subsequent investigations. The following representative profiles were collected: (1) 5 s isometric effort, (2) three consecutive repetitions of traditional leg press exercise performed at normal movement velocity and (3) three consecutive repetitions of coupled concentric-eccentric leg press exercise with pneumatic resistance supplementing the concentric load during the eccentric phase. The eccentric repetitions were performed with slow tempo for safety purposes due to heavy load and the concentric phase was performed explosively.

4.2.4 Data Analysis

Validity of the pneumatic function of the device was determined using linear regression analysis, which explored the relationship between measurements obtained from instrumentation and the standards provided by the manufacturer, for each of the 14 dial increments. The average of the difference between measurements ± 95% confidence intervals (CI), expressed as a percentage, was calculated to support this data. Reproducibility of measurements of force imposed by pneumatic technology was assessed using the percentage difference between two measurements taken on separate occasions. Values were calculated for each load increment. Representative profiles for eccentric, traditional and isometric exercise on the device were created using kinetic and kinematic data extracted from the instrumentations data acquisition software and converted to graphs using GraphPad Software (GraphPad Software Inc., Version 8.0, California, USA).

4.3 Results

The similarity in the measurements of the imposed force to the manufacturer's standard is shown in Figure 4.3.1. The mean difference between the two measurements for all load increments was: 0.7 ± 1.0% (95% CI: 0.2 to 1.18%). However, these data do not account for the carriage load; the system load for each of the dial increments are shown in Table 4.3.1. Overall, the percentage difference between repeated measurements was -0.1 ± 1.4%. With the addition of the instrumentation, the foot carriage imposed a force that was equivalent to ~139 kg (Table 4.3.1).

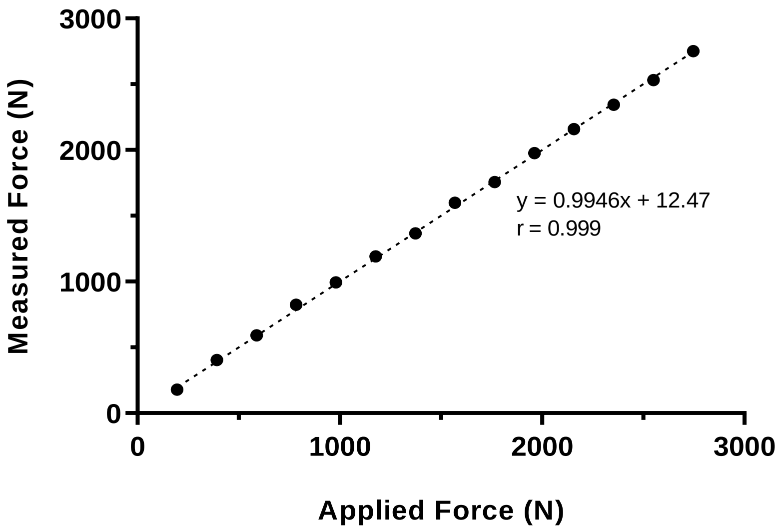

Figure 4.3.1. The relationship between measurements of imposed force compared to the manufacturer's standard.

When using the device in isometric function, there was some carriage movement upon the application of force prior to firmly locking into place. The representative force and displacement profile for a single isometric effort displayed in Figure 4.3.2 illustrates this. The displacement of the carriage was ~1.5 cm and occurred regardless of the chosen position along the machine's framework.

Table 4.3.1. Repeatability measurements of imposed force for the carriage load and each of the load increments offered by pneumatic technology.

Dial No.	$\bar{x}$ ± SD (N)	$\bar{x}$ ± SD (kg)	$\%_{diff}$
0	1362 ± 6	139 ± 1	1.3
0.5	1519 ± 13	155 ± 1	0.9
1	1762 ± 26	180 ± 3	0.7
1.5	1942 ± 10	198 ± 1	0.5
2	2194 ± 25	224 ± 3	1.3
2.5	2337 ± 47	238 ± 5	1.2
3	2562 ± 13	261 ± 1	0.9
3.5	2731 ± 24	278 ± 2	1.1
4	2962 ± 41	302 ± 4	1.1
4.5	3103 ± 31	316 ± 3	0.4
5	3340 ± 1	340 ± 0	0.8
5.5	3508 ± 8	358 ± 1	0.2
6	3706 ± 5	378 ± 1	0.4
6.5	3887 ± 41	396 ± 4	0.6
7	4128 ± 2	421 ± 0	0.8

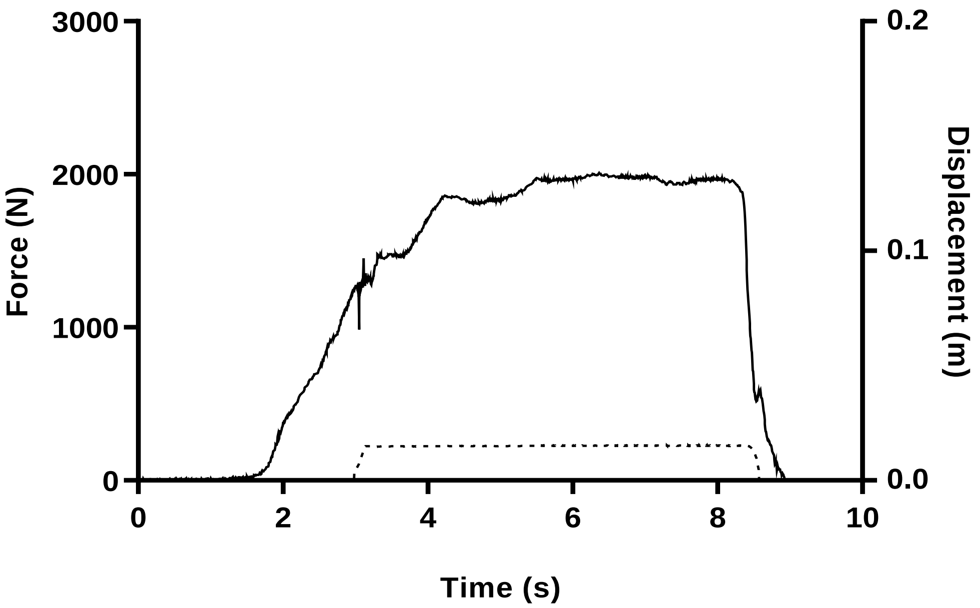

Figure 4.3.2. Force-time profile for an isometric effort showing small disruption to the force-time curve at x = 3. Dashed black line represents displacement, black solid line represents force.

A representative force, displacement and velocity profile for three consecutive repetitions of traditional leg press exercise performed at normal movement velocity is shown in Figure 4.3.3A. A representative force, displacement and velocity profile for three consecutive repetitions of coupled concentric-eccentric leg press exercise with pneumatic resistance supplementing the concentric load during the eccentric phase is shown in Figure 4.3.3B.

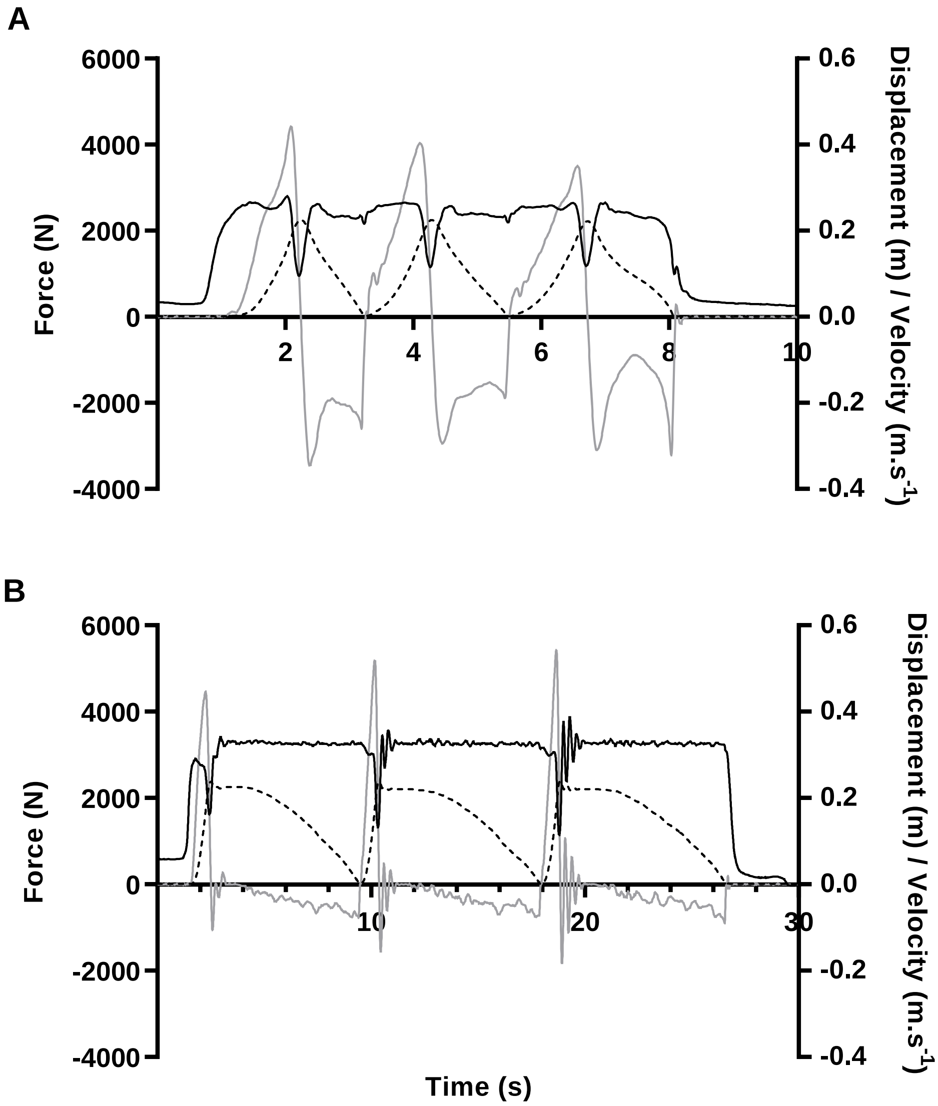

Figure 4.3.3. Representative force-time-displacement profiles for three consecutive repetitions of (A) traditional leg press exercise and (B) coupled concentric-eccentric leg press exercise with pneumatic resistance supplementing the concentric load during the eccentric phase and performed at a 5 s tempo. Dashed black line represents displacement (0 = end ROM 90º knee joint angle), black solid line represents force and grey solid line represents velocity.

4.4 Discussion

The aim of this investigation was to evaluate the function and use of a bespoke leg press device designed for strength training and research. This investigation verified the imposed force offered by the foot carriage and the affixed instrumentation, and the imposed force offered by the pneumatic technology at a range of incremental loads. This ensured accurate and precise application of training and testing loads in subsequent studies. Further to this, the machine was sampled in eccentric and isometric mode to gain an understanding the function of the device when in a non-conventional mode. Importantly, this highlighted potential methodological issues during isometric assessment.

The application of load via pneumatic technology is controlled manually using a dial mechanism which proved to be an efficient, precise and accurate means to apply a range of loads during the eccentric phase of the leg press exercise. The pneumatic technology offers the potential to efficiently load up to an additional ~280 kg to the ~140 kg foot carriage, thus has the capacity to load up to ~420 kg during the descending part of the leg press exercise without the manually addition of weight plates. The additional weight of the force plate equipment contributed to the total load of the foot carriage, which was previously approximated as 90 kg. Consequently, the load during the ascending part of the lift can be no less than ~140 kg, unless measures are put into place to aid this portion of the lift for the performance of EO exercise. Being technology driven, the device removes the logistical constraints that are associated with the manual application and removal of load by several spotters. Hence, this feature overcomes one of the major challenges that is associated with eccentric loading (Tinwala *et al*., 2017). Furthermore, it reduces psychological impact that would occur if seeing a very high load manually applied to the machine, which has been highlighted as a potential issue with a device developed for eccentric overload during squatting (Frohm *et al*., 2005). Overall, the device facilitates the application of high loads during the eccentric phase of a movement in a safe and controlled manner whilst adding and removing the supplementary load very efficiently for smooth transition between the eccentric and concentric phases without the need for spotters or assistance.

There was an almost perfect association between applied and measured forces which confirms the validity of the data acquisition system. There was very minimal variation in repeated application of force despite being a manually controlled dial. This was relatively consistent across the seven incremental load values that were provided by the manufacturer and seven values which were intermediate theoretical values derived from those provided by the manufacturer. These data are comparable to those derived from other specialised eccentric device (Frohm *et al*., 2005). With future use, if the researcher is similarly vigilant with aligning the dial with the intended force value, then minimal variation can be expected when applying loads during training and testing.

The low sampling rate (200 Hz) of the instrumentation could present a limitation for measuring rate of force development (RFD). Low sampling rate has been shown to compromise the reliability of RFD measurements but not peak force (James *et al*., 2017). To improve the device, it is suggested to add instrumentation with higher sampling rate which can be used to assess RFD under eccentric, concentric and isometric conditions. Despite this, the device has the potential to offer novel information pertaining to the mechanical conditions underpinning eccentric exercise on leg press which, in the current form is likely to have greater reliability when assessing maximum force producing capacities.

When functioning as an isometric device, the foot carriage shifts upon the initial application of force. The shift is small (~1.5 cm) after which the carriage firmly locks into the pre-determined latch where it remains until force application is reduced. Although the movement is small, the compliance of the foot carriage compromises the integrity of the hip and knee angle during the isometric assessment. The magnitude of the change in knee and hip joint angle is not known. However, the small concentric action and uncontrolled changes in joint configuration prior to isometric contraction is likely to impact the expression of force due to change in muscle length and the introduction of movement velocity (Maffiuletti *et al*., 2016). Additionally, it is clear in Figure 4.3.2 that the abrupt halt of the carriage after initial force application causes a brief spike in force, influencing the shape of the rising force-time curve. This would impede analysis across this segment of the curve. Hence, contractions with uncontrolled pre-tension or countermovement should be excluded and approaches that ensure minimal compliance are recommended. Notwithstanding, the locking mechanism facilitates a simple and efficient means of switching the machines function to an isometric device, however before further investigations the device needs modification to prevent foot carriage movement upon force application to ensure accuracy and precision during isometric testing and training.

The instrumentation provides the potential to gather valuable information about the mechanical characteristics underpinning different modes of exercise. Preliminary data shows that traditional and eccentric exercise performed the leg press device present visually different mechanical profiles. The representative profiles clearly illustrate that during traditional leg press exercise force output is reduced during the eccentric phase of the exercise in order to lower the foot carriage during the descending phase of the lift (Figure 4.3.3A). Supplementing the load with pneumatic resistance accommodates the higher force producing capacity of eccentrically biased muscle actions, which appears to be sustainable at a relatively slow tempo across multiple repetitions (Figure 4.3.3.B). The mechanical characteristics were investigated in greater detail in Chapter 6.

The application of AEL using the device appears to offer the potential to impact velocity during the concentric phase across consecutive repetitions, whereas it could potentially decrease across consecutive repetitions during traditional leg press exercise. Previously, acute concentric performance enhancement has been attributed to increased neural stimulation, increased preload, increased storage and recovery of elastic energy (Doan *et al*., 2002; Ojasto and Häkkinen, 2009). Given that concentric performance and the rapid transition from eccentric to concentric movement is a primary concern in sports performance, use of this device as an eccentric training tool may be viewed positively by practitioners and coaches. It is understood that these data are descriptive in nature and are yet to undergo more scientifically rigorous investigations. Although some areas are speculative and descriptive, at present these data have provided preliminary evidence of distinct difference between traditional and AEL exercise performed on the leg press device, which was not previously known.

In summary, this device offered an efficient, precise and accurate means to apply a range of loads during the eccentric phase of the leg press exercise. The application of high loads is conducted in a safe and controlled manner without the need for spotters or assistance, thus removing some of the safety concerns associated with eccentric exercise that was highlighted in the previous chapter. The device efficiently switches function to an isometric device but movement in the foot carriage must be reduced before conducting investigation using the mode of assessment. The instrumentation on the machine facilitates the acquisition of mechanical parameters for eccentric, concentric and isometric exercise which can be used to investigate the force potential of different muscle actions. Importantly, the device offers a means of performing high-intensity eccentric exercise and isometric strength assessment safely and efficiently whilst reducing spinal compression.

4.5 Applied Perspective

This exploratory investigation aimed to evaluate the function and use of a bespoke leg press device designed for strength training and research. This specifically addressed the second aim this thesis. Importantly, the leg press device omits some of the logistical issues associated with the application of high-intensity eccentric exercise that were highlighted in Chapter 3. Calibration of the device ensured that the application of training and testing loads used in the remainder of this work were accurate and precise. This inquiry highlighted potential methodological issues during isometric assessment. As a result, modifications were made to ensure that the integrity of desired hip and knee joint angles could be maintained during isometric assessment. Using this modification, the reproducibility of isometric leg press exertions was examined (Chapter 5) to determine thresholds for meaningful change which were used to interpret the effects of eccentric training on isometric maximum strength (Chapter 7 and 9). Sampling the device in eccentric and isometric mode provided a glimpse of the potential of the device as training and evaluation tool. The exploratory nature of this investigation was descriptive in nature but provide preliminary information that was needed to better understand how to use the device for the remainder of this work. Consequently, this work prompted further investigation into the unique mechanical stimulus that is offered when performing eccentric exercise on the device and to understand how it altered with changing conditions (Chapter 6).

Chapter 5

Familiarisation, Reproducibility, Sensitivity and Joint Angle Specificity of Isometric Force Output during Leg Press

5.1 Introduction

To determine the effectiveness of strength training programmes on maximum strength, S&C practitioners must have a means to quantify and ascertain progression of neuromuscular qualities (DeWeese *et al*., 2015a; Sheppard *et al*., 2011). As mentioned in the previous chapter, isometric multi-joint tests are a common method of assessing maximal force capacity. However, the anatomical position required to perform the commonly used isometric squat (Bazyler *et al*., 2015; Blazevich *et al*., 2002; Marcora and Miller, 2000; Verdera *et al*., 1999) and mid-thigh pull (De Witt *et al*., 2018; James *et al*., 2017; Thomas *et al*., 2015) exercises can compromise the trunk and spinal column due to high levels of compression, thus increasing the potential for injury. Isometric assessment performed on the inclined leg press device may provide an alternative solution to facilitate strength evaluation for those athletes unable to adequately or safely perform other isometric assessment modalities. Or simply, it can offer an alternative approach to lower body strength assessment.

To date, there is a paucity of work examining isometric leg press assessment, despite its common use in applied practice. The reliability and validity have been briefly addressed (Dopsaj and Ivanović, 2011; Ivanović and Dopsaj, 2013; Marcora and Miller, 2000; Milic *et al*., 2013; Papadopoulos *et al*., 2013) using equipment far removed from that generally found in an applied contexts. Therefore, it seems apt to address the practicality of isometric leg press tests using comparable equipment and postures that are common among applied practice. To address the third aim of this thesis this investigation aimed to evaluate the efficacy of isometric strength assessment performed on the leg press device (described in detail in the previous chapter). Specifically, this investigation; (1) the effects of familiarisation, (2) the reproducibility and sensitivity of measurements of isometric force output during strength assessment and, (2) the effects on force output when altering the angle at the knee joint. These factors helped to determine the suitability of isometric leg press tests as a tool for monitoring and neuromuscular evaluation in performance settings and importantly, as part of the evaluation procedures following eccentric exercise performed as part of this work.

5.2 Methods

5.2.1 Experimental Approach

A within-subjects, repeated measures design was used to investigate the effects of familiarisation and reproducibility of force output during isometric assessment at 90º and 120º knee-joint angle (ISO_{90} and ISO_{120}, respectively, where 180º = full joint extension). Participants attended the laboratory on three separate occasions; familiarisation (T_1), test (T_2) and retest (T_3), separated by 7 days. During each session, ISO_{90} and ISO_{120} was assessed in a randomised order. All sessions were identical to allow investigation into the reproducibility of peak force output at each knee-joint angle. Data were collected during T_1 to determine initial learning effects and during T_2 and T_3 to determine the reproducibility and sensitivity of measurements of isometric force output.

5.2.2 Participants

Thirty-five strength-trained males (mean ± SD age, stature and body mass: 31 ± 5 years, 178 ± 8 cm and 85 ± 13 kg, respectively) volunteered to participate in this study. All participants completed the three required sessions but of the 35 participants, data for T_1 were collected for twenty-three participants only, but data were collected for all 35 participants during T_2 and T_3. Put simply, twelve data sets from the thirty-five participants were not attained at T_1. The mean resistance training history was 13 ± 6 years with a background of strength-power sport (e.g. rugby, combat, powerlifting, Olympic weightlifting, track sprint cycling, athletics). All participants were free from musculoskeletal injury with no history of musculoskeletal, neuromuscular or cardiovascular disorders. The volunteers were asked to avoid unaccustomed and strenuous exercise prior to and between the testing sessions. They were instructed to attend each session in a fed and well-hydrated, and to keep this consistent routine (nutrition, sleep and general exercise) throughout the testing period and specifically in the 48 hours prior to each testing session. Repeated testing was kept to the same time of day to minimise the influence of diurnal variation. All study procedures and requirements were outlined and discussed prior to the participants providing written, informed consent. Ethical approval was granted by Northumbria University Research Ethics committee in accordance with The Declaration of Helsinki.

5.2.3 Warm-up

Prior to testing, a standardised warm-up was completed using a cycle ergometer (Wattbike Pro, Wattbike Ltd., Nottingham, UK). Participants were asked to pedal at 70-80 revolutions·min^{-1} maintaining between 110-120 W for five minutes. Immediately following this, five minutes of dynamic mobility exercises were completed to target the trunk, hips and lower limbs. This was followed by eight, six and four repetitions of leg press exercise at an external intensity equivalent to 70, 85 and 100% of body mass, respectively. Each set was separated by two minutes.

5.2.4 Isometric Force Assessment

Maximum isometric force assessment was performed on leg press device detailed in previous chapter (Figure 4.2.1). To determine maximum isometric force output, the leg press foot carriage was secured to ensure the required knee-joint angle (90° or 120°, verified by goniometry). In line with the outcomes of the investigation comprising Chapter 4, ratchet straps (> 600 kg limit) were used to fix the carriage firmly in place to prevent unwanted movement and to maintain the integrity of knee and hip joint angle throughout the isometric assessment (Figure 5.2.1).

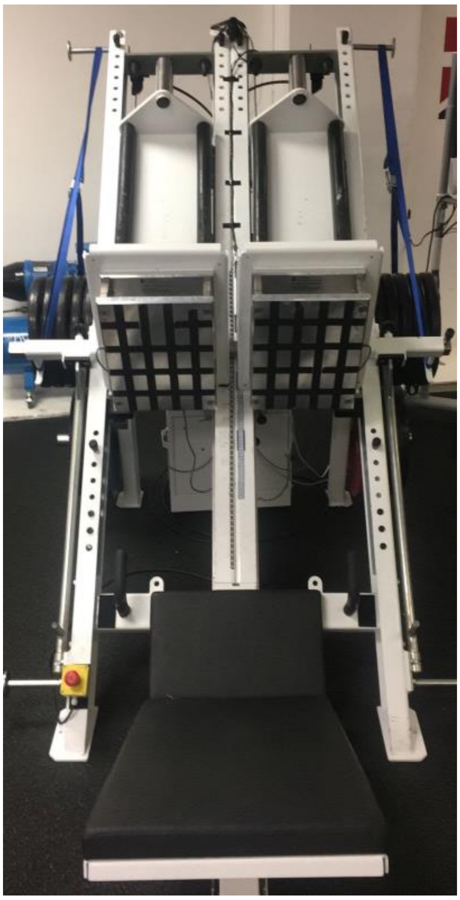

Figure 5.2.1. Ratchet straps secured to the device to prevent movement of the foot carriage whilst in isometric function.

The joint angles were chosen as they are commonly used for isometric assessment (Marcora and Miller, 2000; Zaras *et al*., 2016). Additionally, the 90° angle was chosen as it reflects the angle at the end range of motion (ROM) common to coupled eccentric-concentric exercise and the 120° knee angle optimised absolute peak force, based on usual practice, pilot testing and information from professional S&C coaches at the English Institute of Sport. An example of the body position during ISO_{120} assessment is shown in Figure 5.2.2.

Figure 5.2.2. An example of the position required for the ISO_{120} assessment.

For each isometric assessment two preparatory efforts were conducted; one performed at 50% and one performed at 75% perceived effort, separated by 30 seconds. Testing consisted of three maximal efforts each with a duration of five seconds and interspersed by three minutes, for each knee-joint position. Testing between ISO_{90} and ISO_{120} was separated by 10 minutes to reduce the influence of fatigue. During each effort, participants were advised to 'progressively build up force towards pushing as hard as possible until instructed to stop'. The same strong verbal encouragement was provided for all efforts. Unilateral force measures were summed to reflect the bilateral nature of the exercise. The trial with the highest peak force for the ISO_{90} and the ISO_{120} assessment was used for analysis.

5.2.5 Data Analysis

All data sets were checked for normality using Shapiro Wilk's test ($p \leq 0.05$) and homoscedacity using Levene's test ($p \leq 0.05$). These checks will be performed before similar analysis in all forthcoming chapters, where appropriate. To examine the effects of familiarisation, a repeated measures ANOVA was used to determine statistical difference in force output between the three sessions (T_1, T_2, T_3, $n = 23$) for $IS0_{90}$ and ISO_{120}, and if required followed by a Bonferroni *post-hoc* test. Additionally, a paired samples t-test was used to determine statistical difference in force output between T_2 and T_3 for $n = 35$ for $IS0_{90}$ and ISO_{120}, separately. To examine the reproducibility of peak force measurement between T_1 and T_2, T_2 and T_3 for $n = 23$, T_2 and T_3 for $n = 35$, the change in the mean ($\Delta\,\bar{x}$), intraclass correlation coefficient (ICC), coefficient of variation ($CV = \frac{SD_{within-subject}}{\bar{x}} \times 100$), typical error ($TE = \frac{SD_{diff}}{\sqrt{2}}$), (Lexell and Downham, 2005) were calculated. The 95% CI were included for $\Delta\,\bar{x}$ and CV. The smallest worthwhile change ($SWC = 0.2 \times SD_{between-subjects}$) was established to determine thresholds that signifies the smallest meaningful change in performance (Hopkins, 2004).

A paired samples t-test was used to identify statistical difference in force output between $IS0_{90}$ and ISO_{120}. For each participant, the magnitude of differences in force output between $IS0_{90}$ and ISO_{120} was calculated. Pearson's correlation analysis was used to establish the relationship between the magnitude of differences in force output between $IS0_{90}$ and ISO_{120} and ISO_{90} and ISO_{120}, separately. Statistical significance was set at alpha level (α) $p \leq 0.05$, a-priori. All analyses were conducted using Excel (Microsoft Office, 2010) and SPSS (Version 24.0; SPSS Inc., Chicago, USA) software. The calculation of reliability parameters and effect sizes, significance threshold and software to perform analysis is consistent with this information in all forthcoming chapters. Unless stated otherwise.

5.3 Results

Using a sample size of $n = 23$, ISO_{90} force output was similar across all three sessions; T_1: 2861 ± 724 N (95% CI: 2548, 3174), T_2: 2898 ± 731 N (95% CI: 2582, 3214) and T_3: 2830 ± 666 N (95% CI: 2542, 3118, $F_{2,\,44} = 1.02$, $p = 0.37$,

η_p^2 = 0.04). Alike, ISO_{120} force output was similar across all three sessions; T_1: 5667 ± 1664 N (95% CI: 4947, 6387), T_2: 5748 ± 1652 N (95% CI: 5033, 6462) and T_3: 5651 ± 1642 N (95% CI: 4941, 6361, $F_{2,44}$ = 4.06, p = 0.67, η_p^2 = 0.02). Using a sample size of n = 35, ISO_{90} force output was similar between T_2: 2668 ± 629 N (95% CI: 2460, 2876) and T_3: 2653 ± 571 N (95% CI: 2463, 2842, $t_{(34)}$ = 0.55, p = 0.59, d = 0.01). Alike, ISO_{120} force output was similar between T_2: 5172 ± 1443 N (95% CI: 4694, 5650) and T_3: 5134 ± 1469 N (95% CI: 4647, 5621, $t_{(34)}$ = 0.58, p = 0.57, d = 0.03). Measurements taken during ISO_{90} and ISO_{120} assessments demonstrated a good degree of reproducibility (Table 5.3.1); when using a sample size of n = 23, reproducibility of peak force associated with T_2 and T_3 were improved compared to those associated with T_1 and T_2. However, when using a larger sample size of n = 35 the reproducibility of peak force associated with T_2 and T_3 showed further improvement. Measurement noise was less that the criteria for detecting meaningful change in performance in the first instance at T_2 and T_3 for ISO_{90} using the sample size n = 23 and ISO_{120} using the sample size n = 35

Table 5.3.1. Reproducibility of peak force measurements during ISO_{90} and ISO_{120} assessment across three sessions.

	ISO_{90}			ISO_{120}		
	T_1-T_2 n = 23	**T_2-T_3** n = 23	**T_2-T_3** n = 35	**T_1-T_2** n = 23	**T_2-T_3** n = 23	**T_2-T_3** n = 35
$\Delta \bar{x}$ (%)	1.3 (-1.6, 4.2)	-2.3 (-4.6, 0.6)	-0.6 (-2.3, 2.0)	1.4 (-2.7, 5.4)	-1.7 (-4.9, 1.5)	-0.7 (-3.3, 1.6)
CV (%)	4.2 (2.8, 5.2)	3.7 (2.6, 4.9)	3.4 (2.4, 4.4)	5.6 (3.6, 7.2)	5.1 (3.5, 5.9)	4.2 (3.1, 5.1)
TE (%)	5.7	4.4	4.4	7.8	6.4	5.4
SWC (%)	5.0	4.8	4.5	5.7	5.7	5.6
ICC	0.95	0.97	0.96	0.93	0.95	0.96

Values in brackets represent lower and upper 95% CI.

Force output was joint angle specific; ISO_{120}: 5153 ± 1443 N (95% CI: 4674, 5632) and ISO_{90}: 2660 ± 595 N (95% CI: 2463, 2858) ($t_{(34)}$ = 14.1, p < 0.001). In all cases, force output during ISO_{120} exceeded force output during ISO_{90}. The relationship between force output between $IS0_{90}$ and ISO_{120} was strong; r = 0.78 (p < 0.001). However, the differences in force output between joint angles for individual subjects were not consistent and ranged from 697 N to 5805 N (Figure

5.3.1). The disparity in force output was strongly related to the force producing capacity during ISO_{120} (r = 0.93) as opposed to ISO_{90} (r = 0.50).

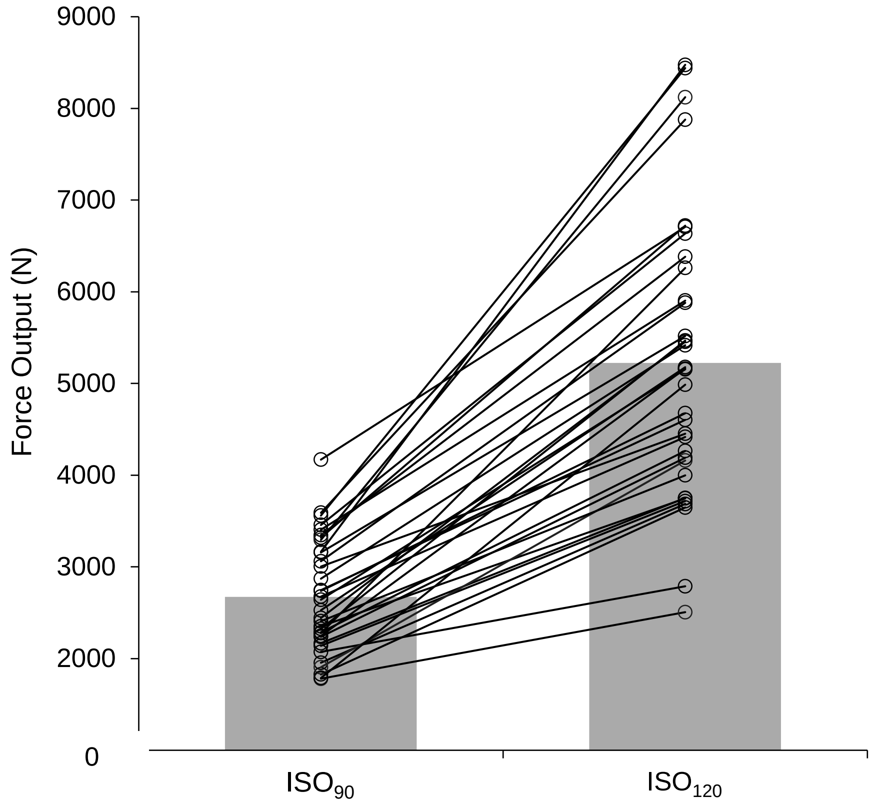

Figure 5.3.1. A paired-data scatterplot displaying isometric force output at 90° and 120° knee joint-angle. Grey bars represent mean values.

5.4 Discussion

The aim of this investigation was to evaluate the efficacy of isometric strength assessment performed on a leg press device. Specifically, this investigation established; (1) the effects of familiarisation, (2) the reproducibility and sensitivity of measurements of isometric force output during strength assessment and, (2) the effects on force output when altering angle at the knee joint. The main findings of this study was that isometric assessment performed on a leg press device required minimal habituation to demonstrate a good degree of reproducibility. It is a simple and practical method to evaluate strength at different joint angles, which highlight intra-subject variability in joint-angle specific force output.

Isometric strength performance was relatively stable from the first session, although familiarisation served to increase the reproducibility of peak force measurements across subsequent sessions. After a single familiarisation session, the measurements demonstrated a good degree of reproducibility. Importantly, these data align with the reproducibility (ICC: 0.92-0.99) of other isometric leg press devices (Ivanović and Dopsaj, 2013; Papadopoulos *et al*., 2013), whilst being consistent with the absolute and relative reproducibility of more established methods frequently used in applied practice; isometric mid-thigh pull; ICC: > 0.96, CV: < 4% (James *et al*., 2017; Thomas *et al*., 2015) and isometric squat; ICC: 0.89-0.99, CV: ~4% (Bazyler *et al*., 2015; Drake *et al*., 2018). In the current study the CV, including CIs, compared favourably (< 5%) when based on previous assessments (Green *et al*., 2017; James *et al*., 2017). It is important to highlight that measuring performance across a greater number of sessions might augmented reproducibility indices further. Notwithstanding, based on the current data, isometric assessment performed on a leg press device requires minimal habituation to demonstrate a good degree of reproducibility and therefore can be considered an efficient and relatively stable means to evaluate lower body strength.

The SWC exceeded the error and variability associated with each test and therefore demonstrate that the ISO_{90} and ISO_{120} assessments are “lower-noise” methods that can be used to detect changes in performance. The SWC offers criteria that is marginally in excess of the error of the test and requires changes in performance of 4-6% to be classified as *meaningful*. The capacity of a test to detect small changes in performance increases the practicality of the test, especially in athletic contexts where small improvements are considered to be higher valued (Hopkins, 2004). However, a 4-6% change in maximal force producing capacity when assessing highly-strength-trained individuals and experienced athletes is not likely to be considered a small change. Consequently, using this threshold could be demanding relatively substantial changes in performance when already operating at a high level. Unfortunately, the sample size that is deemed appropriate for a reliability study has resulted in the gathering of a relatively heterogeneous sample. This would have affected the threshold for SWC which considers the between-subjects SD. Using the TE which accounts for the within-subject variance could therefore be a somewhat more appropriate threshold to take from these data. Ideally, an exclusive assessment of between-session variability with a group of athletes would be conducted and used to interpret changes in their performance following subsequent training blocks. This would compromise on sample size but would be more practically applicable when applying the information in an applied context. Unfortunately, this is a limitation of this study and, as a consequence a somewhat inflated threshold will be used in subsequent studies with more homogeneous populations. Nonetheless, TE can be taken from this investigation in an attempt to minimise the inflated thresholds for denoting meaningful change.

The assessment of strength at two different positions enabled the quantification of joint angle specificity of force output. Altering the knee joint angle by 30º resulted in a ~50% change in force producing capacity, although the magnitude of change of force output demonstrated large intra-individual variation. On a group level, the finding is comparable to others (45-55%) who have employed similar joint angle constraints during 1 RM back squat (Marcora and Miller, 2000) and isometric horizontal leg press assessment (Drinkwater *et al*., 2012). Differences in force output are attributable to changes in the muscle length-tension relationship and the alteration of muscle moment arm length imposed by the body segment orientation (Demura *et al*., 2010). Intuitively, one might expect ISO_{90} to have a greater force generating capacity than ISO_{120} given the length-tension relationship of the knee flexors; however, multi-joint exercises such as the leg press incorporate numerous muscle groups (gluteal, hamstrings and triceps surae, for example) that also contribute force production. Whilst we cannot ascertain the contribution of each muscle group to overall force production, this work highlights that more extended knee positions during an inclined leg press task generates greater force than when positioned at 90°. From a broader perspective, it is important to consider the task being assessed and the potential contributions being made by different muscle groups and hence the lever arm moments in multi-joint exercise, like the inclined leg press, might outweigh optimal cross-bridge formation of individual muscle groups.

Consequently, these data highlight the different qualities of isometric force expression during an inclined leg press activity. More specifically, ISO_{120} employs a mechanically advantageous joint configuration and is perhaps more indicative of an individual’s maximum force generating capability. Conversely, ISO_{90}

employs a less mechanically advantageous joint configuration and, whilst still a measure of maximum force capacity, it detects an individual's ability to exert force when in a more restricted position, which is arguably more representative of the joints lower force generating capacity. Importantly, the magnitude of the difference in force output between joint angles show large intra-subject variability (Figure 5.3.1) and appears to be largely associated with force capacity at 120° knee joint angle. Thus, attaining individual isometric strength profiles at multiple joint angles allows practitioners to observe the extent to which an individual can apply force at different positions. This enables a greater insight into the training needs of the individual to guide exercise prescription.

In summary, isometric efforts performed on an incline leg press machine allows the assessment of coordinated lower limb, multi-joint assessment. This method has a high degree of practicality to examine isometric strength, especially for those with a high injury risk, such as compromised by spinal loading or inability to competently conduct the required position during other lower-limb multi-joint exercises. In addition, administration of the isometric tests is simple, time efficient, and require minimal skill to perform. Although it is lacking in some sensitivity to detect small changes in force output in a high-performance perspective.

5.5 Applied Perspective

This investigation specifically addresses the second aim of this thesis, which was to evaluate the efficacy of isometric strength assessment performed on a leg press device. The investigation established the suitability of isometric leg press tests as a tool for monitoring and neuromuscular evaluation in performance settings and importantly, as part of the evaluation procedures following eccentric exercise performed as part of this work (Chapter 7 and 9). Although a 4-6% change in maximal force producing capacity when assessing highly-strength-trained individuals and experienced athletes is not likely to be considered a small change, it is a starting point for the purpose of this research. Broady, it highlights the implications before it can be optimally implemented in applied practice. The feedback from the participants during assessment enabled a better understanding of the approach required to effectively perform the assessment with individuals of different nature. Given the efficiency and practicality of isometric strength assessment, ISO_{90} was used as a basis to prescribe supramaximal eccentric load for the experimental investigation in Chapter 6. Additionally, this investigation has enhanced our understanding of lower body, multi-joint isometric force production. This prompted further investigation into task-specificity of lower body force output (Chapter 8) in order to better understand how force output is affected with changing conditions, and how it relates to the observations of joint angle specificity of force output observed in this investigation.

Chapter 6

An Evaluation of Supramaximally Loaded Eccentric Leg Press Exercise

6.1 Introduction

As mentioned in Chapter 4, the application of high-intensity eccentric training in a performance environment is fraught with problems. The logistical constraints and limitations associated with practical application have led to a paucity of information about this activity in an applied context, and importantly, the potential to understand the application for training prescription and adaptation. Modification of the inclined leg press device removed the potential limitations, such that it was possible to apply very high loads eccentrically. An indication of the unique stimulus offered by high-intensity exercise performed on the device was provided in Chapter 4. However, it was necessary to gain a more complete understanding of the nature of the stimulus, such that could be used effectively for subsequent investigations.

Given the paucity of evidence-based information pertaining to guidance for eccentric training protocol, it is important to gain a greater insight into the unique mechanical stimulus offered by high-intensity eccentric exercise to be able to devise appropriate and effective protocol for enhancing neuromuscular function and muscle tissue qualities. The prescription of load would appear to be the most important variable to consider for strength adaptation. However the applied load, *per se*, might be less informative than the kinematics and kinetics associated with how the load is moved (Crewther *et al*., 2005). A better understanding of how a high-intensity load is moved would help to optimise the performance, evaluation and prescription of high-intensity eccentric exercise, and as a consequence, improve the application for this work and in S&C practice. To our knowledge, no study has investigated the mechanical stimulus of supramaximal intensity eccentric exercise using a method that can be replicated in an applied training environment. Therefore, the aim of this investigation was to evaluate the mechanical response to high-intensity eccentric exercise and understand how it alters with changing conditions. This specifically addresses the fourth aim of this thesis.

6.2 Methods

6.2.1 Experimental Approach

This study used a within-subject, repeated measures design to investigate the mechanical profile of three different supramaximally loaded eccentric exercise conditions; low (LO), moderate (MOD) and high (HI) intensity performed on the leg press device (Chapter 4, Figure 4.2.1). Participants attended four testing sessions performing one session per week, on the same day and at the same time each week to avoid the influence of diurnal fluctuations. Session 1 included familiarisation of ISO_{90} and following a 10 minutes rest interval, assessment of ISO_{90} to attain a baseline for eccentric load prescription. Sessions 2, 3 and 4 included the assessment of eccentric repetition characteristics under each loading condition; LO, MOD and HI in a randomised, counterbalanced order. The magnitude of external load applied to LO, MOD and HI conditions were equivalent in intensity to 110%, 130% and 150% of ISO_{90}, respectively. The exercise was performed as a coupled concentric-eccentric movement whereby the concentric phase was performed with a load equivalent to 1.5 times bodyweight. This approach to loading allowed standardisation of the concentric phase due to the relatively high load of the carriage relative to some participants bodyweight.

6.2.2 Participants

Fifteen males (mean ± SD; 31 ± 7 years, 180.0 ± 6.8 cm and 81.5 ±13.9 kg, respectively) volunteered to participate in this study. All participants were from a strength-power sport background, e.g., Olympic weightlifting, rugby, athletics and track sprint cycling, with 11 ± 7 years of resistance training experience which had included several phases of maximum strength training. Details of participant injury history, pre-test requirements, testing procedures and ethical approval details are consistent with those outlined in section 5.2.2.

6.2.3 Isometric Force Assessment Familiarisation and Testing

Following the general warm-up which was conducted according to the procedures outlined in section 5.2.3, participants were familiarised with the isometric assessment protocol. Securing the leg press carriage at 90° of the participants knee flexion (verified by goniometry), they completed three separate three seconds efforts at; 50%, 75% and 100% of perceived effort. Each effort was separated by 30 seconds, with two minutes between each intensity. Ten minutes after the familiarisation ISO_{90} was assessed using the procedures outlined in section 5.2.4. Assessment of ISO_{90} was conducted in the same session after familiarisation as it was established in chapter 5 that the assessment requires minimal skill to perform to attain reproducible measurements.

6.2.4 Eccentric Familiarisation and Assessment

Familiarisation procedures for high-intensity eccentric exercise, based on pilot testing, consisted of three sets of three repetitions with an external load equivalent to 75% and 85% of ISO_{90}, and three sets of one repetition with an external load equivalent to 100% of ISO_{90}. All repetitions performed during familiarisation were performed with a five seconds tempo. All sets were separated by three minutes. Following familiarisation and the general warm-up (which was conducted according to the procedures outlined in section 5.2.3), participants completed an incremental eccentric preparation task to become accustomed to the heavier loads and thus reducing the potential for injury. Preparation included two repetitions with an external load equivalent to 75% and 100% of ISO_{90}, respectively. An additional one repetition with an external load equivalent to 100%, 110% and 130% of ISO_{90} was completed preceding the LO, MOD and HI trial, respectively. All repetitions performed during the incremental preparation task lasted three seconds.

Eccentric assessment comprised of four separate repetitions at either LO (100% of ISO_{90}), MOD (130% of ISO_{90}) or HI (150% of ISO_{90}) intensity, with each repetition separated by five minutes to minimise the effects of fatigue. Each session was randomly assigned either LO, MOD or HI intensity. Load prescription for each condition was calculated from maximum force output during ISO_{90}. A version of this assessment has previously been shown to have a strong correlation with conventional 1 RM (Mcguigan *et al*., 2010). Therefore, instead of using conventional 1 RM, ISO_{90} was used as administration of the tests is simple, time efficient and requires minimal skill to perform to attain reproducible measurements, according to the findings outlined in Chapter 5. The eccentric exercise range of motion (ROM) moved through 80° at the knee joint, reaching the end ROM at 90° knee flexion. Moving to the same end ROM meant that the exercise was limited to strength capacity at the same joint angle as ISO_{90}. The range of intensities were chosen to ensure that manipulation in external load was sufficiently different enough to produce mechanical differences in the kinetic and kinematic parameters to be able to draw meaningful conclusions for use in coaching and research practice.

The performance requirements of the eccentric exercise were to; 1) halt the supplementary load before initiating any lowering action; 2) initiate lowering action slowly with control and execute with consistent, but self-selected tempo across the ROM; 3) resist the carriage from accelerating downwards throughout the ROM; 4) react rapidly as the eccentric load is withdrawn to push the carriage upwards to promote continued force production throughout the whole ROM and to prevent loss of muscular control and dropping the carriage to the safety stops. The same verbal encouragement was provided throughout each testing session.

The following variables were collected; average force (N), end force (N), TUT (s), average velocity ($m \cdot s^{-1}$), and average acceleration ($m \cdot s^{-2}$). These data were captured between the start of the repetition (maximum displacement of the foot carriage = 170° knee joint angle) and the end of the repetition (zero displacement of the foot carriage = 90° knee joint angle). These were the locations that corresponded with the application and removal of the added eccentric load. For each condition, the trial that most satisfied the performance requirements were taken for analysis. Force data for the left and right side were summed to reflect the bilateral nature of the exercise.

6.2.5 Data Analysis

The reproducibility of eccentric repetition performance was determined using ICC and CV including 95% CI, which were calculated using the procedures outlined in section 5.2.5. From the raw data, acceleration was calculated manually using the first derivative of velocity: $\frac{dv}{dt}$ where v = velocity and t = time. Using SPSS (Version 24.0; SPSS Inc, Chicago, USA) a repeated measures ANOVA was used to determine significant differences in force output (average across the repetition and at the instand of end ROM), TUT, velocity and acceleration between each loading condition and where appropriate, a Bonferroni *post-hoc* test was conducted. Group data are presented as $\bar{x}$ ± SD with 95% CI. Data are supported with partial eta squared ($\eta_p{}^2$) effect sizes, α was set at $p \leq 0.05$, *a-priori*.

6.3 Results

The ICC and CV data revealed excellent within session reliability for average force. Although ICC data for TUT demonstrated an excellent degree of reliability, performance between repetitions showed variability. These data are displayed in Table 6.3.1.

Table 6.3.1. Reproducibility of measurements of average force and TUT during LO, MOD and HI loading conditions across separate repetitions.

	LO		MOD		HI	
	Av.Force (N)	**TUT (s)**	**Av.Force (N)**	**TUT (s)**	**Av.Force (N)**	**TUT (s)**
ICC	1.00 (1.00, 1.00)	0.96(0.90,0.99)	1.00 (1.00, 1.00)	0.95 (0.86, 0.98)	1.00 (1.00, 1.00)	0.98 (0.94, 0.99)
CV (%)	0.9 (0.6, 1.2)	7.5 (5.1. 9.9)	0.8 (0.6, 1.1)	8.6 (5.9, 11.4)	0.52 (0.35, 0.68)	5.9 (5.9, 11.4)
p	0.17	0.69	0.41	0.53	0.98	0.65

The results show that ISO_{90} peak force equated to 2794 ± 812 N (95% CI: 2326, 3263 N). Average force associated with each loading conditions exceeded ISO_{90} but was less than the prescribed external force. This meant that the actual intensity of each loading condition was equivalent in intensity to 101 ± 4% (95% CI: 98, 103%), 116 ± 4% (95% CI: 114, 118%) and 132 ± 8% (95% CI: 128, 137%) for LO, MOD and HI, respectively. All loading conditions demonstrated a similar pattern of mechanical profile (Figure 6.3.1), however, the variables underpinning each profile showed significant ($p < 0.01$) load dependent response (LO vs MOD, MOD vs HI, LO vs HI) for all variables, except for average acceleration which was significantly different between LO and HI, only ($p = 0.05$, Table 6.3.2). Force at the end ROM was 1%, 3% and 5% less than the average force measured over the ROM for LO, MOD and HI trials respectively.

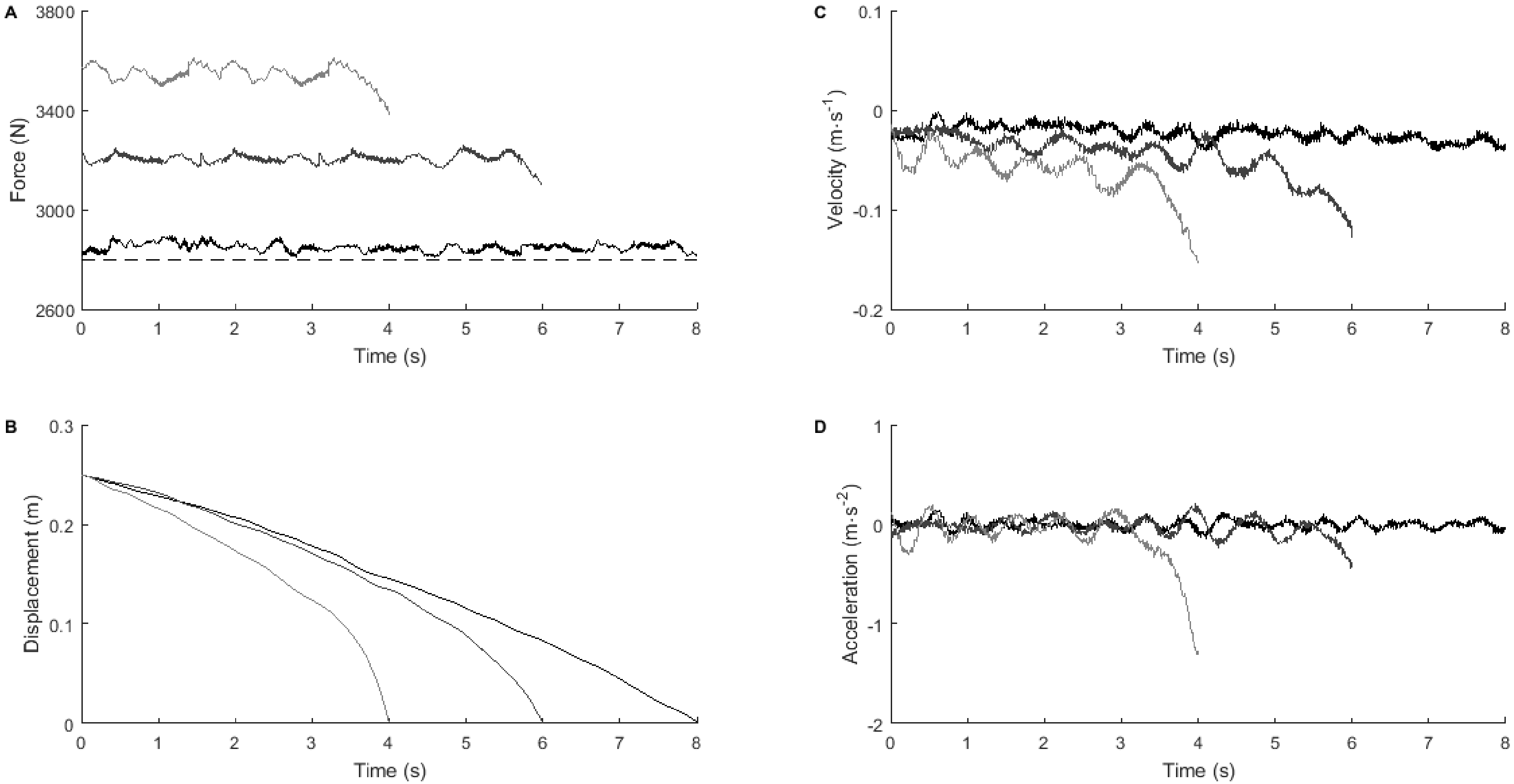

Figure 6.3.1. A representative mechanical profile for a single eccentric leg press repetition under three supramaximal loading conditions. Black solid line: LO intensity loading condition, dark grey solid line: MOD intensity loading condition, light grey solid line: HI intensity loading condition, dashed black line: IMVC at 90° knee flexion. A: force-time profile, B: displacement-time profile, C: velocity-time profile, D: acceleration-time profile.

Table 6.3.2. Mechanical characteristics of eccentric leg press repetitions during LO, MOD and HI intensity loading conditions

	LO			MOD			HI			ANOVA		
		95% CI			95% CI			95% CI		Significance		
Variable	**Mean ± SD**	**LCI - UCI**		**Mean ± SD**	**LCI - UCI**		**Mean ± SD**	**LCI - UCI**		*p*	**F**	η_p^2
Prescribed Force (N)	3074 ± 893	2579 - 3568	***b,c***	3633 ± 1055	3048 - 4217	***a,c***	4192 ± 1218	3517 - 4866	***a,b***	< 0.01	177.7	0.93
Av. Force (N)	2813 ± 833	2351 - 3274	***b,c***	3240 ± 873	2757 - 3723	***a,c***	3626 ± 858	3151 - 4101	***a,b***	< 0.01	285.2	0.95
End Force (N)	2795 ± 811	2346 - 3244	***b,c***	3148 ± 850	2677 - 3619	***a,c***	3447 ± 799	3004 - 3889	***a,b***	< 0.01	287.8	0.95
TUT (s)	8.1 ± 2.2	6.9 - 9.3	***b,c***	6.0 ± 1.5	5.2 - 6.8	***a,c***	4.4 ± 1.0	3.9 - 5.0	***a,b***	< 0.01	51.0	0.78
Av. Velocity ($m{\cdot}s^{-1}$)	-0.03 ± 0.01	-0.03 - -0.04	***b,c***	-0.04 ± 0.01	-0.03 - -0.05	***a,c***	-0.06 ± 0.02	-0.05 - -0.07	***a,b***	< 0.01	25.7	0.65
Av. Acceleration ($m{\cdot}s^{-2}$)	-0.002 ± 0.002	-0.003 - 0.000	***c****	-0.003 ± 0.004	-0.005 - 0.000		-0.008 ± 0.010	-0.013 - -0.002	***a****	0.05	4.2	0.23

a **= sig diff from LO,** ***b*** **= sig diff from MOD,** ***c*** **= sig diff from HI at alpha level** ***p*** **< 0.01 (****p*** **< 0.05)**

6.4 Discussion

The aim of this investigation was to evaluate the mechanical response to high-intensity eccentric exercise and understand how it alters with changing conditions. The results showed that the heavier relative external load stimulated greater average force output which, in turn, was associated with a faster descent velocity and shorter TUT. With each increment in external load (LO vs MOD, MOD vs HI) average force output increased ~12% and average descent velocity increased by ~35%, which was equivalent to a decrease in TUT of ~26%. The eccentric force output under each loading condition was less than the force imposed by the external load. As a result, the intensity of the supramaximal load was less than the prescribed 110%, 130% and 150% relative to peak force exerted during the ISO_{90}. Each condition displayed a similar mechanical profile throughout the ROM, but with the heavier external load a decrease in force output and concomitant increase in velocity and acceleration was prominent towards the end ROM (Figure 6.3.1).

In this study, supramaximal eccentric exercise was employed to explore the strength potential of eccentric actions without the limitation of concentric force producing capacity. The eccentric protocol focused on actively limiting the downwards acceleration of the foot carriage such that it descended under control. This eccentric movement has minimal involvement of the SSC (Higbie *et al.,* 1996) and the slow nature of this exercise perhaps lacks task-specificity to some sports (Wagle *et al*., 2017). However, the extended TUT at high levels of force exceeds what can be achieved with traditional resistance exercise. Given that a mechanical stimuli is integral to induce adaptation (Hortobágyi *et al*., 1996a), the application of very high loads facilitated through eccentric exercise could provide a potentially powerful stimulus for musculoskeletal adaptation. Hence, this training approach could provide a novel training stimulus to experienced athletes potent enough to stimulate an adaptive response required to enhance performance potential. However, a greater understanding of different force-time interactions is warranted to inform the prescription of different variations of eccentric training, particularly given the growing interest in elite sport to maximise adaptation from eccentric loading. Training load resources outlining the relationship between repetitions and load, similar to that provided by the National Strength and Conditioning Association for conventional exercise, would undoubtedly assist practitioners in implementing session-by-session exercise prescription. This investigation has addressed the early stages of such a resource and future research should consider evolving this approach to assist practitioners with the programming of high-intensity eccentric exercise in athletes S&C regimes.

The force-time traces showed that the eccentric protocol induced a relatively stable force output across most of the working range (Figure 6.3.1A). Because of this feature, average force was used to quantify the relative intensity of each eccentric effort. On this basis, the intensity of each loading condition equated to ~101, ~116 and ~132% of ISO_{90}. The disparity in prescribed versus actual load is attributed to the voluntary reduction in force output in order to allow the foot carriage to descend. In all conditions force of the external load and muscle exerted by the participant were not equal; but the slower the intended velocity of the descent, the closer the force expressed by the subject is to equalling the force imposed by the load (Schilling *et al*., 2008). Therefore, in the absence of instrumentation, when training with slower velocities the external load would provide a good representation of the magnitude of the force being exerted. The opposite is true for repetitions with faster descent velocity, whereby faster velocities will be more distant from the applied load.

Under these intensities, the higher loading conditions tended to show a force decline towards the end ROM (Figure 6.3.1A). This indicates that the force of the applied external load became too great to resist at the same target velocity. This resulted in downwards acceleration of the foot carriage towards the end of the ROM. It is important to be mindful of these changes in acceleration at higher intensities if the intention of the training stimulus is to provide an even and stable stimulus throughout the working range. Previously, practitioners and researchers have used a 3% decline in force as a cut-off criterion to ensure the provision of a stable stimulus (Refsnes, 1999). When applying this criterion to these data, the LO trial showed a decline in force output of 1%, MOD declined by 3% and the HI declined by 5%. Based on the above criterion, the efforts under the HI loading condition might not be acceptable. Nonetheless, the force output in the HI condition generated a great deal of muscle tension, so if the aim is to load an athlete with similar loads, practitioners should be mindful that the load is not well tolerated in more flexed positions which could have implications for safe execution of the movement.

From a broader perspective, fast muscle lengthening under very high tension could exacerbate EIMD (Morgan and Allen, 1999). In more flexed joint positions antagonist muscles are operating at longer lengths, causing several sarcomeres to lengthen on the descending limb of the length-tension curve. Hence, changes in acceleration towards the end ROM may incur a greater degree of muscle damage from forcibly lengthening the muscle at fast velocity. Therefore, S&C coaches should be mindful of performance towards the end ROM as this could have implications on physical status in the days following the intervention and impede athlete performance during other aspects of training.

The prescription of eccentric load intensity for each condition used angle specific isometric assessment. Using this method, individuals tended to exhibit different performance responses to the same relative load. This could be expected given that that neural control strategies during eccentric and isometric actions are different (Enoka, 1996b). As such, it seems apt to consider task-specific methods of eccentric assessment or inclusion of a target tempo or movement velocity to reduce variability in repeated performance and to standardise performance between individuals. This would enable practitioners to accurately determine an individual's eccentric force producing capacity and prescribe eccentric training more accurately. Notwithstanding, using the isometric method as a basis for load prescription enabled successful implementation of three different supramaximal eccentric exercise protocols.

In summary, supramaximally loaded eccentric exercise appears to offer a unique and potent stimulus; individuals can be exposed to extended TUT at high levels of force that exceed what more traditional regimes might offer. However, when implementing supramaximal loaded eccentric exercise, practitioners should be mindful to prescribe a load that is well tolerated in the restricted portion (end ROM) of the exercise movement to facilitate continued force production and maintenance of muscular tension for consistent movement. From an applied perspective, this information has offered practitioners an understanding of the training stimulus provided on similar devices when prescribing, implementing or evaluating high-intensity eccentric exercise in their research and practice. Importantly, these data provide new insight into the performance response from strength-trained individuals throughout supramaximal eccentric leg press exercise which can be used as a basis to develop appropriate protocol for similar populations.

6.5 Applied Perspective

The aim of this investigation was to evaluate the mechanical response to high-intensity eccentric exercise and understand how it alters with changing conditions. This investigation specifically addresses the fourth aim of this thesis. This segment of the work enabled a better understanding of the mechanics underpinning high-intensity eccentric exercise such that the exercise could be coached and performed more effectively, as well as prescribed and implemented more appropriately. This formed the framework for a more meticulous application of high-intensity eccentric exercise which underpinned performance of the protocol for the studies conducted in the series of investigations comprising this work. Given that there was evidence of individual variation in self-selected TUT of repetitions, a target tempo was used in subsequent investigations to standardise performance between individuals when performing bouts of high-intensity eccentric exercise (Chapter 7). As a result of conducting the testing, there was a tendency for participants to spend a longer duration moving through the top ROM versus the bottom ROM where the exercise becomes more difficult. Although these repetitions were not picked for inclusion in the main analysis, it highlighted that visual markers must be incorporated with a target tempo to ensure smooth and consistent movement throughout the ROM and therefore more meticulous standardisation between individuals.

Chapter 7

The Acute Alteration in Muscle Function, Architecture and Morphology Following High-Intensity Eccentric Exercise

7.1 Introduction

Immediate and short-term impairment in muscle function is typically experienced following traditional modes of high-intensity resistance exercise (McCaulley *et al*., 2009; Walker *et al*., 2012). Similarly, high-intensity eccentric exercise often results in transiently impaired muscle function (Cheung *et al*., 2003; Clarkson *et al*., 1992; Howatson *et al*., 2007; Hunter *et al*., 2012). The physiological response underpinning impaired central and peripheral function can result in distinct neuromuscular and morphological adaptation (McKune *et al*., 2012) which can serve to increase muscle strength, power and hypertrophy. To attain these desired adaptations, it is important that S&C practitioners prescribe eccentric exercise to athletes with sufficient intensity to prompt muscle tissue regeneration and growth, and progress neuromuscular function but does not result in unnecessary, excessive and detrimental muscle soreness which can leave physical performance severely diminished and training is negatively impacted for several days. This could increase the propensity of non-functional overreaching.

In order to effectively administer high-intensity eccentric exercise, it is necessary to understand the acute impact of a training stimulus. Increasing the awareness of the acute responses to eccentric stimuli will enable practitioners to better understand how high-intensity, multi-joint eccentric resistance exercise can be used as a training tool to enhance aspects of physical performance. More specifically, quantifying the acute impact and evaluating tolerances to exercise can assist in estimating the time needed for recovery, optimising the acute training stimulus, informing the overall management of the training stimulus within a broader performance programme and indicating the training adaptations that could be expected from habitual use of the exercise (Gathercole *et al*., 2015; de Paula Simola *et al*., 2015; Ronglan *et al*., 2006; Thorlund *et al*., 2008). Therefore, the aim of this investigation was to gain an insight into the immediate exercise-induced alteration in muscle function and muscle ultrastructure following an initial and repeated bout of high-intensity eccentric resistance exercise. This specifically addresses the fifth aim of this thesis.

7.2 Methods

7.2.1 Experimental Approach

This investigation used a within-subjects, repeated measures design. Participants were required to visit the facility on three separate occasions. Each visit was separated by seven days. The first visit was for familiarisation of the components of the testing battery and the eccentric exercise technique (procedures are outlined in section 6.2.3 and 6.2.4). The remaining two visits (session 1; S_1 and session 2; S_2) were identical and comprised of neuromuscular and morphological assessments immediately before (PRE) and after (POST) a prescribed bout of high-intensity eccentric exercise. Before performing the prescribed bout of eccentric exercise (referred to as PRE_1 and PRE_2), the order of the assessments were; (1) ultrasonography of VL muscle for morphological and architectural measurements, (2) tensiomyography (TMG) for assessment of VL involuntary muscle contractile function, (3) vertical jump performance for assessment of dynamic performance, and (4) ISO_{90} and ISO_{120} for assessment of isometric strength. After performing the prescribed bout of eccentric exercise ($POST_1$ and $POST_2$) these assessments were conducted in the reverse order.

The order was to ensure minimal disruption of the measurements taken across the different assessments. Collecting data at these time-points and performing and initial and repeated bout of high-intensity eccentric exercise provided the opportunity to; (1) determine the within-session change of measurements for S_1 and S_2, (2) establish the difference in the magnitude of the within-session change between S_1 and S_2, (3) indicate the return to baseline for all measurements 7 days after the initial bout of exercise and, (4) combine the data in order to characterise the acute response to high-intensity eccentric exercise.

7.2.2 Participants

Fourteen males (mean ± SD age, stature and body mass: 30 ± 4 years, 178.0 ± 7.9 cm, 87.4 ± 13.8 kg and, respectively) volunteered to participate in this study. Participants were from a strength-power sport background, e.g. Olympic weightlifting, rugby, athletics, American football and combat, with 11 ± 4 years of resistance training experience. Details of participant injury history, pre-test requirements, testing procedures and ethical approval details are consistent with those outlined in section 5.2.2.

7.2.3 Muscle Morphology

B-mode ultrasonography images were obtained with an extended field of view linear-array probe (10 cm) using a Hitachi EUB 8500 device (Hitachi Medical Corporation, Tokyo, Japan) to determine PA (angle between the muscle fascicle and the deep aponeurosis), FL (length of the fascicular path between the deep and superficial aponeuroses), MT (distance between the deep and superficial aponeuroses) and CSA (area inside the muscle border) of the VL muscle. To determine PA, FL and MT, echo-absorptive markers were placed perpendicular to the line of the femur at 50% (MID) and 25% (DIST) locations along the femur and 50% of muscle width. The probe was aligned parallel to the line of the femur and positioned across each marker to capture images at the desired locations. To determine CSA, several echo-absorptive markers were placed parallel to the line of the femur at 50% and 25% along the femur length, in accordance with the locations for muscle architecture. Each marker was spaced three centimetres apart and the series of markers spanned across the width of the muscle. The probe was aligned perpendicular to the line of the femur starting at the medial border of the muscle and was moved slowly around the leg to the lateral border of the VL muscle. During movement, two echo absorptive markers and the femur were always in view on screen with the femur located in the bottom centre of the image between the shadows cast by the markers. For all scans, probe application pressure was kept minimal to ensure the least possible muscle distortion.

Participants were evaluated in a supine position with the legs relaxed and positioned at 120º knee joint angle (180° = full extension) using a cushion support. Water-soluble transmission gel was used on the skin and scanning probe to aid acoustic coupling. To promote repeatability of measurements, the scanning locations, anatomical reference points (i.e., bony landmarks), distinctive skin markings (i.e., freckles and scars) were mapped on a flexible plastic sheet (Baroni *et al*., 2013). The screen of the ultrasound device was recorded onto a laptop computer using a H.264 Pro Recorder (Blackmagic Design, Australia) to capture real-time recording of each scan for the investigator to re-visit the scans and select the most appropriate still image from a frame by frame review to ensure the best image was used for analysis. For CSA analysis, still images from each 3 cm interval were aligned using the shadows cast by the echo-absorptive markers to form the outline of the muscle in a single image (Adobe Photoshop CC, Version 19.0). Still images were analysed using ImageJ software (National Institutes of Health, USA). When the length of a fascicle extended beyond the border of the image, linear continuation of the fascicle and aponeurosis was assumed (Hicks *et al*., 2013). Repeatability of measurements (n = 10) on two separate occasions were established prior to this investigation (Table 7.2.1). The data were in line with those reported elsewhere (Kwah *et al*., 2013; Noorkoiv *et al*., 2010).

Table 7.2.1. Between-session reliability of measurements of VL muscle architecture and morphology.

Variable	$\bar{x}$ ± SD	$\bar{x}$ ± SD	$\Delta\bar{x}$ (%)	ICC (95% CI)	TE	CV (%)	SWC (%)
FL_{MID} (cm)	8.2 ± 1.0	8.1 ± 1.0	0.8	0.97 (0.89-0.99)	0.2	2.0	2.4
FL_{DIST} (cm)	10.8 ± 2.0	10.7 ± 1.8	0.0	0.97 (0.88-0.99)	0.4	3.3	3.4
PA_{MID} (°)	19.0 ± 1.8	19.4 ± 2.1	-1.8	0.90 (0.66-0.97)	0.4	3.1	2.0
PA_{DIST} (°)	20.9 ± 2.7	20.9 ± 2.7	-0.2	0.98 (0.92-1.00)	0.4	2.0	2.6
MT_{MID} (cm)	2.6 ± 0.4	2.6 ± 0.4	-0.1	0.98 (0.93-1.00)	0.1	1.9	2.7
MT_{DIST} (cm)	2.3 ± 0.4	2.3 ± 0.3	-0.1	0.98 (0.90-0.99)	0.1	2.4	2.8
CSA_{MID} (cm^2)	33.1 ± 7.2	33.4 ± 7.4	-0.8	1.00 (0.99-1.00)	0.3	1.0	4.4
CSA_{DIST} (cm^2)	11.9 ± 3.9	11.9 ± 3.8	0.1	0.99 (0.98-1.00)	0.3	2.5	6.4

FL = fascicle length, PA = pennation angle, MT = muscle thickness, CSA = cross-sectional area, MID = middle, DIST = distal, $\bar{x}$ = group mean, SD = standard deviation, $\Delta\bar{x}$ = change in the group mean, ICC = intraclass correlation coefficient, CI = confidence interval, TE = typical error, CV = coefficient of variation, SWC = smallest worthwhile change.

7.2.4 Muscle Contractile Function

Measurements of muscle contractile function were acquired using tensiomyography (TMG–BMC Ltd., Ljubljana). TMG measures radial deformation of the muscle belly following a stimulated muscle contraction to provide information about its contractile properties (Macgregor *et al*., 2018). The methods of assessment were in accordance with previously established procedures (Ditroilo *et al*., 2013; Macgregor *et al*., 2016). In the same supine position and knee joint configuration as that during ultrasound scanning, the TMG digital displacement transducer was placed perpendicular to the thickest part of the VL muscle. The initial pressure applied by the sensor was controlled by ensuring the spring-loaded probe was retracted to 50% of its length prior to administering electrical stimulation. The initial position of the sensor was verified to ensure that the highest mechanical response with the least amount of co-activation was achieved upon providing electrical stimulation. Coactivation was characterised by a second peak in the displacement-time curve. If there was evidence of co-activation, the position of the transducer was adjusted slightly. The two stimulating electrodes, each 5 cm^2 (Axelgaard, USA) were placed on the skin surface located 2.5 cm either side of the sensor and towards the proximal and distal ends of the VL. Once the transducers and electrodes were in the correct position marks were made on the skin using a permanent marker pen and were recorded on the flexible plastic sheet (described in the previous section) to promote reproducibility of measurements across the separate testing occasions.

Starting at a current of 20 mA, a single 1 ms electrical stimulation was administered. The stimulus was increased in increments of 10 mA until maximal contractile response was obtained. A 10 s pause separated each stimulus to minimise the potential for interference from previous stimulations. The TMG software provided measurements of muscle belly displacement (D_m; the magnitude of radial deformation of the muscle belly during contraction), contraction time (T_c; the time between 10% and 90% of D_m) and delay time (T_d; time taken from onset on electrical stimulation to 10% of D_m). Muscle contraction velocity (V_c) was calculated manually using the following calculation: $V_c = D_m/T_c$, where D_m is taken between 10% and 90% of maximal D_m and T_c is the time between 10% and 90% of D_m. This is in line with procedures used elsewhere (Macgregor *et al*., 2016). An annotated representative displacement-time profile is displayed in Figure 7.2.1.

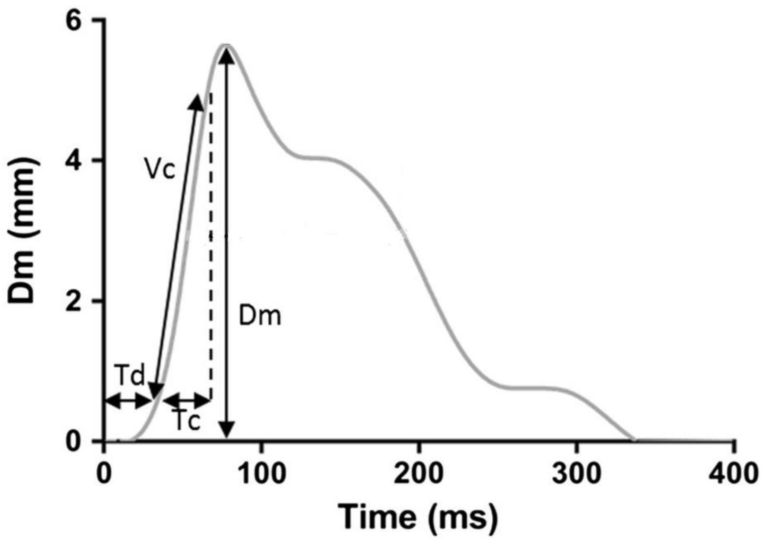

Figure 7.2.1. Parameters extracted from a TMG displacement-time curve. Adapted from Macgregor *et al.* (2016).

The electrodes were unplugged but left in place and secured with tape to ensure precision of measurements taken pre- and post- exercise. Repeatability of measurements (*n* = 10) on two separate occasions were established prior to this investigation (Table 7.2.2). The data are in line with those reported elsewhere (Macgregor *et al*., 2018).

Table 7.2.2. Between-session reliability of measurements of VL muscle contractile properties

Variable	$\bar{x}$ ± SD	$\bar{x}$ ± SD	$\Delta\bar{x}$ (%)	ICC (95% CI)	TE	CV (%)	SWC (%)
D_m (mm)	5.61 ± 1.96	5.57 ± 2.23	0.6	0.95 (0.80-0.99)	0.5	9.2	7.4
T_c (ms)	24.7 ± 2.75	24.8 ± 2.61	-0.1	0.94 (0.87-0.99)	0.7	2.8	2.1
T_d (ms)	22.9 ± 1.46	23.2 ± 2.03	-1.4	0.78 (0.36-0.94)	0.8	3.6	1.4
V_c (mm/ms)	0.12 ± 0.04	0.12 ± 0.04	3.4	0.97 (0.87-0.99)	0.0	5.9	6.2

Dm = muscle belly displacement, Tc = contraction time, Td = delay time, Vc = contraction velocity, $\bar{x}$ = group mean, SD = standard deviation, $\Delta\bar{x}$ = change in the group mean, ICC = intraclass correlation coefficient, CI = confidence interval, TE = typical error, CV = coefficient of variation, SWC = smallest worthwhile change

7.2.5 Vertical Jump Performance

Following the general warm-up which was conducted according to the procedures outlined in section 5.2.3, each participant performed two preparatory efforts for squat jump (SJ) and two preparatory efforts for countermovement jump (CMJ), performed at 50% and 75% of perceived maximum effort which were separated by 10 seconds. Testing consisted of three maximal effort SJ and CMJ. Each jump was separated by 15 seconds and testing for each jump type was separated by three minutes (Bridgeman *et al*., 2017). Both jumps were intended towards jumping as high as possible and to land in the same location as take-off. The CMJ began in a standing position with hip and knee joint at full extension. The jump was initiated by rapid flexion of the hip and knee to a self-selected depth and rapid triple extension of the hip, knee and ankle. The SJ began in a half squat position with knee angle at 90° (measured by goniometry) and held for three seconds (verbally counted by the investigator) prior to performing rapid extension of the hip, knee and ankle to perform the jump. Both jumps did not include an arm swing. Instead, a lightweight wooden stick was held across the shoulders (as if performing the back-squat exercise). For the SJ, the integrity of the knee joint angle was ensured by adjusting the rack, which houses the force plate, to correspond to the height of the wooden stick when the participant was positioned with their knee joint flexed to 90º. The location of the rack was recorded, and the same set-up was used for the testing across the sessions.

The SJ and CMJ were performed on a force platform (400 Series, Fitness Technology, Australia) with a linear position transducer (PT5A, Fitness Technology, Australia) which was secured above the force platform. The cord of the linear position transducer was attached to the mid-point of the wooden stick. When the stick was positioned on the shoulders of the participant, the cord would run in a vertical path directly downwards from the transducer. The system sampled at 1000 Hz. Data were analysed using Ballistic Measurement System software (Version 1: 2015, Fitness Technology, Australia) using a criterion of 50 N above bodyweight to define the start of the jump. Variables of interest were peak force (PF), peak velocity (PV) and jump height derived from peak velocity (JH). Repeatability of measurements (n = 10) on two separate occasions were established prior to this investigation (Table 7.2.3). The data were in line with those reported elsewhere (Markovic *et al*., 2004).

Table 7.2.3. Between-session reliability of CMJ and SJ performance characteristics

Variable	$\bar{x}$ ± SD	$\bar{x}$ ± SD	$\Delta\bar{x}$ (%)	ICC (95% CI)	TE	CV (%)	SWC (%)
CMJ_F (N)	2150 ± 356	2193 ± 349	-2.0	0.98 (0.89-0.99)	47.8	2.2	3.2
SJ_F (N)	1995 ± 294	2017 ± 307	-1.1	0.98 (0.92-0.99)	44.5	2.2	3.0
CMJ_V (m/s)	3.05 ± 0.29	3.02 ± 0.33	0.9	0.95 (0.83-0.99)	0.07	2.3	2.0
SJ_V (m/s)	2.40 ± 0.37	2.41 ± 0.37	-0.7	0.97 (0.88-0.99)	0.07	2.9	3.0
CMJ_H (m)	0.45 ± 0.10	0.45 ± 0.11	0.3	0.97 (0.89-0.99)	0.02	4.2	4.6
SJ_H (m)	0.33 ± 0.08	0.33 ± 0.09	0.8	0.96 (0.85-0.99)	0.02	4.9	5.0

CMJ = countermovement jump, SJ = squat jump, F = peak force, V = peak velocity, H = height, $\bar{x}$ = group mean, SD = standard deviation, $\Delta\bar{x}$ = change in the group mean, ICC = intraclass correlation coefficient, CI = confidence interval, TE = typical error, CV = coefficient of variation, SWC = smallest worthwhile change.

7.2.6 Isometric Force Assessment

The procedures for assessing ISO_{90} and ISO_{120} are outlined in section 5.2.4. Repeatability of measurements using these methods are detailed in Chapter 5 (Table 5.3.1).

7.2.7 Eccentric Exercise

The incremental preparation regime performed prior to the prescribed bout of eccentric exercise is outlined in section 6.2.4. The prescribed eccentric exercise bout comprised of five sets of eight repetitions of coupled eccentric-concentric leg press exercise. Each set was separated by five minutes. The set-repetition scheme was a representation of those successfully implemented in previous experimental studies (see Chapter 2). The external load applied during the descending (eccentric) phase was equivalent to 110% of peak force that was achieved during the ISO_{90} assessment. This approach to eccentric load prescription was the same as the approach used in Chapter 6. The external load applied during the ascending (concentric) phase was equivalent to 1.5 x bodyweight. In this instance, bodyweight was used as a basis for loading as it was more time efficient than performing a traditional 1 RM assessment. The target duration of the descending phase was five seconds, which was standardised using a metronome and visual markers along the machine's framework. The concentric phase was performed in an explosive manner. The device was pre-set to 'unload' at the end of the descending phase (90° at the knee joint). As a result, the 'unload' mechanism ensured that the ROM was standardised. The prescription of the intensity, tempo and ROM was based on the procedures and outcomes following the investigation comprising Chapter 6.

7.2.8 Data Analysis

The procedures for checking data prior to analysis are outlined in section 5.2.5. Paired samples t-tests were used to determine statistically significant differences in; (1) between-session pre-test measurements (PRE_1 vs. PRE_2), (2) within-session measurements for the initial and repeated bout of exercise (PRE_1 vs. $POST_1$; PRE_2 vs. $POST_2$), (3) magnitude of the within-session change in measurements between the initial and repeated bout of exercise (ΔS_1 vs. ΔS_2) and, (4) within-session change in measurements when the data from both sessions were pooled (PRE_{pooled} vs. $POST_{pooled}$). An alpha of $p \leq 0.05$ was considered statistically significant for all comparisons. To interpret the magnitude of the difference between comparisons, Hedges (*g)* effect sizes were calculated:

$$g = \frac{\bar{x}_1 - \bar{x}_2}{SD_{pooled}}$$

This calculation was followed up using an adjustment to account for the small sample size (Hedges and Olkin, 2014). The thresholds for effect size interpretation were; small, moderate, large and very large for 0.2, 0.6, 1.2, 2.0, respectively (Hopkins, 2000). The variation in the magnitudes of individual within-session responses (expressed as a percentage of the respective pre-test value) between the initial and repeated bout of exercise (ΔS_1 and ΔS_2) were displayed using a series of paired data scatterplots. Data from S_1 and S_2 were pooled and the relative differences in measurements were calculated (PRE_{pooled} vs. $POST_{pooled}$) to characterise the acute response to high-intensity eccentric exercise. These data were displayed using a forest plot.

7.3 Results

Table 7.3.1 displays the within-session change in measurements of isometric strength, vertical jump performance and VL muscle contractile properties, and the between-session comparisons of the magnitude of within-session change for these measurements. Measurements of ISO_{90}, ISO_{120}, SJ_H, SJ_V, T_d, D_m and V_c showed a statistically significant decrease following the initial and repeated bout of the prescribed eccentric exercise and were associated with *small* or *small-to-moderate* effect sizes. SJ_F was associated with a *small* effect size following both sessions, despite not demonstrating statistically significant difference between measurements. Collectively, the relative magnitude of change during S_1 and S_2 for ISO_{90}, ISO_{120}, SJ_F, SJ_H, SJ_V, T_d, D_m and V_c exceeded the margin of error associated with each measurement. The between-session comparison of the magnitude of within-session change for measurements of isometric strength, vertical jump performance and VL muscle contractile properties did not demonstrate statistically significant differences and were mostly associated with *trivial* effect sizes. Only ISO_{120}, SJ_H, SJ_V and T_d were associated with *small* or *small-to-moderate* effect sizes.

Table 7.3.2 displays the within-session change in measurements of VL muscle architecture and morphology, and the between-session comparisons of the magnitude of within-session change for these measurements. FL_{DIST} was the only variable to demonstrate a statistically significant difference following the prescribed eccentric exercise. This result was following the initial bout of the prescribed eccentric exercise (S_1) but not the repeated bout (S_2). However, the associated effect sizes were *small* for both S_1 and S_2. PA_{MID} and PA_{DIST} were associated with *small* effect sizes following the repeated bout only (S_2), despite not demonstrating statistically significant difference between measurements. For the variables FL_{DIST} and MT_{DIST} the relative magnitude of change exceeded the margin of error associated with each measurement during S_1 and S_2. For the variables FL_{MID}, PA_{DIST} and CSA_{DIST} the relative magnitude of change exceeded the margin of error associated with each measurement during S_2, only**.** The between-session comparison of the magnitude of within-session change for measurements of VL muscle architectural and morphological measurements did not demonstrate statistically significant differences and were mostly associated with *trivial* effect sizes. Only measurements of FL_{MID}, PA_{MID} and PA_{DIST} were associated with *small* effect sizes.

The between-session comparisons of measurements taken PRE- and POST-exercise are displayed in Table 7.3.3 for isometric strength and vertical jump performance, Table 7.3.4 for VL muscle architecture and VL muscle morphology, and Table 7.3.5 for VL muscle contractile properties. These data indicate that for all variables, measurements taken PRE- and POST-exercise were not statistically significantly different between S_1 and S_2. The effect sizes associated with most of the variables were *trivial*. Although, PRE-exercise measurements for SJ_F, T_d and PA_{MID} and POST-exercise measurements for SJ_F and PA_{DIST} were associated with *small* effect sizes. The relative difference in the mean values for between repeated measurements of SJ_F, PA_{MID} and CSA_{DIST} taken PRE-exercise exceeded the respective measurement error, which was established in previous investigation (refer to Table 5.3.1, Table 7.2.1, Table 7.2.2 and Table 7.2.3). Generally, for most of the variables the within-subjects SD between repeated measurements (TE) taken PRE-exercise was inflated compared to that derived from the assessment of reliability.

Data from the initial and repeated session were pooled (PRE_{pooled} vs. $POST_{pooled}$) and the overall acute characteristic response to high-intensity eccentric exercise is displayed in Figure 7.3.1. Several aspects of the data have implied that individuals demonstrated varied responses to the initial and repeated bout of the prescribed eccentric exercise. Figure 7.3.2 displays paired data scatterplots to illustrate the varied individual responses pertaining to isometric strength and vertical jump performance. Figure 7.3.3 displays paired data scatterplots to illustrate the varied individual responses pertaining to VL muscle architecture and morphology.

Table 7.3.1. Within-session change in measurements of isometric strength, vertical jump performance and the contractile properties of the VL muscle and the between-session comparisons of the magnitude of within-session change.

		PRE	POST	Within-Session Comparisons (PRE vs. POST)				Between-Session Comparisons (ΔS_1 vs. ΔS_2)			
Variable		**$\bar{x}$ ± SD**	**$\bar{x}$ ± SD**	**$\bar{x}_{diff}$ ± SD (%)**	***t***	***p***	***g***	**$\bar{x}$ ± SD (%)**	**t**	***p***	***g* [95% CI]**
ISO_{90} (N)	S_1	2486 ± 541	2213 ± 400	-273 ± 299 (9.8 ± 11.0)	-3.42	0.01	-0.6 [-1.3, 0.2]	-40 ± 185 (1.3 ± 7.6)	-0.81	0.43	-0.1 [-0.9, 0.6]
	S_2	2494 ± 482	2261 ± 378	-233 ± 276 (8.4 ± 10.6)	-3.16	0.01	-0.5 [-1.3, 0.2]				
ISO_{120} (N)	S_1	4856 ± 1433	4007 ± 1082	-849 ± 947 (15.8 ± 15.7)	-3.35	0.01	-0.6 [-1.4, 0.1]	-239 ± 803 (4.3 ± 14.7)	-1.12	0.28	-0.3 [-1.0, 0.5]
	S_2	4843 ± 1323	4234 ± 1191	-609 ± 728 (11.5 ± 14.9)	-3.13	0.01	-0.5 [-1.2, 0.3]				
CMJ_F (N)	S_1	1995 ± 286	1971 ± 276	-24 ± 94 (1.1 ± 4.6)	-0.88	0.40	-0.1 [-0.9, 0.8]	16 ± 85 (0.7 ± 4.1)	0.64	0.53	0.1 [-0.7, 0.9]
	S_2	2020 ± 297	1980 ± 275	-40 ± 111 (1.7 ± 5.1)	-1.23	0.24	-0.1 [-1.0, 0.7]				
CMJ_H (m)	S_1	0.45 ± 0.10	0.44 ± 0.08	-0.01 ± 0.05 (2.0 ± 12.0)	-0.50	0.63	-0.1 [-1.0, 0.7]	-0.01 ± 0.05 (0.4 ± 12.2)	-0.40	0.70	-0.1 [-0.9, 0.7]
	S_2	0.45 ± 0.10	0.44 ± 0.09	-0.01 ± 0.04 (1.6 ± 9.2)	-0.58	0.58	-0.1 [-0.9, 0.7]				
CMJ_V (m/s)	S_1	2.95 ± 0.31	2.91 ± 0.26	-0.04 ± 0.18 (1.2 ± 6.0)	-0.84	0.42	-0.1 [-0.9, 0.7]	-0.01 ± 0.17 (0.3 ± 5.9)	-0.23	0.82	-0.1 [-0.8, 0.7]
	S_2	2.95 ± 0.32	2.92 ± 0.30	-0.03 ± 0.13 (0.9 ± 4.6)	-0.88	0.40	-0.1 [-0.9, 0.7]				
SJ_F (N)	S_1	2118 ± 333	2026 ± 298	-91 ± 294 (3.5 ± 12.4)	-1.12	0.28	-0.3 [-1.1, 0.5]	31 ± 254 (0.8 ± 11.2)	0.45	0.66	0.1 [-0.7, 0.6]
	S_2	2220 ± 379	2097 ± 202	-123 ± 241 (4.3 ± 8.6)	-1.84	0.09	-0.4 [-1.2, 0.4]				
SJ_H (m)	S_1	0.32 ± 0.07	0.29 ± 0.08	-0.03 ± 0.04 (9.6 ± 12.2)	-2.59	0.02	-0.4 [-1.2, 0.4]	-0.01 ± 0.04 (3.0 ± 12.1)	-0.64	0.53	-0.2 [-0.9, 0.6]
	S_2	0.32 ± 0.09	0.29 ± 0.08	-0.02 ± 0.03 (6.5 ± 9.5)	-2.84	0.01	-0.3 [-1.1, 0.5]				
SJ_V (m/s)	S_1	2.49 ± 0.29	2.36 ± 0.33	-0.13 ± 0.17 (5.1 ± 6.6)	-2.69	0.02	-0.4 [-1.2, 0.4]	-0.03 ± 0.15 (1.7 ± 6.3)	-0.84	0.42	-0.2 [-1.0, 0.5]
	S_2	2.47 ± 0.35	2.38 ± 0.32	-0.09 ± 0.13 (3.4 ± 5.1)	-2.64	0.02	-0.3 [-1.0, 0.5]				
T_d (ms)	S_1	23.7 ± 1.9	21.2 ± 1.5	-2.5 ± 1.3 (10.2 ± 5.0)	-6.89	0.00	-1.4 [-2.2, -0.5]	-0.8 ± 2.0 (3.0 ± 7.9)	-1.45	0.17	-0.6 [-1.4, 0.1]
	S_2	23.3 ± 1.5	21.6 ± 1.8	-1.7 ± 1.2 (7.1 ± 4.8)	-5.32	0.00	-1.0 [-1.8, -0.1]				
D_m (mm)	S_1	5.5 ± 2.2	4.5 ± 1.6	-1.0 ± 1.2 (16.0 ± 19.3)	-3.15	0.01	-0.5 [-1.3, 0.3]	0.0 ± 0.9 (2.0 ± 18.5)	0.17	0.87	0.0 [-0.7, 0.8]
	S_2	5.4 ± 2.1	4.4 ± 1.7	-1.0 ± 1.1 (18.0 ± 18.9)	-3.70	0.00	-0.5 [-1.3, 0.3]				
V_c (mm/ms)	S_1	0.11 ± 0.04	0.10 ± 0.03	-0.02 ± 0.02 (13.0 ± 19.1)	-2.33	0.04	-0.4 [-1.2, 0.3]	0.00 ± 0.02 (4.1 ± 18.4)	0.70	0.50	0.1 [-0.6, 0.9]
	S_2	0.11 ± 0.04	0.09 ± 0.04	-0.02 ± 0.03 (17.1 ± 23.1)	-2.89	0.01	-0.5 [-1.3, 0.3]				

Table 7.3.2. Within-session change in measurements of muscle architecture and morphology and the between-session comparisons of the magnitude of within-session change.

		PRE	POST	Within-Session Comparisons (PRE vs. POST)				Between-Session Comparisons (ΔS_1 vs. ΔS_2)			
Variable		**$\bar{x}$ ± SD**	**$\bar{x}$ ± SD**	**$\bar{x}_{diff}$ ± SD (%)**	***t***	***p***	***g***	**$\bar{x}$ ± SD (%)**	**t**	***p***	***g* [95% CI]**
FL_{MID} (cm)	S_1	8.3 ± 1.2	8.4 ± 1.1	0.1 ± 0.7 (1.5 ± 9.0)	0.39	0.70	0.1 [-0.7, 0.8]	0.2 ± 0.5 (2.6 ± 7.0)	1.37	0.19	0.3 [-0.5, 1.0]
	S_2	8.2 ± 1.4	8.5 ± 1.2	0.3 ± 0.8 (4.1 ± 10.7)	1.30	0.22	0.2 [-0.6, 1.0]				
FL_{DIST} (cm)	S_1	10.2 ± 2.1	11.1 ± 2.4	0.8 ± 1.3 (8.7 ± 14.1)	2.30	0.04	0.3 [-0.4, 1.1]	-0.2 ± 1.1 (2.1 ± 12.0)	-0.64	0.54	-0.1 [-0.9, 0.6]
	S_2	10.5 ± 1.9	11.1 ± 2.2	0.6 ± 1.4 (6.6 ± 14.0)	1.74	0.11	0.3 [-0.5, 1.1]				
PA_{MID} (°)	S_1	18.3 ± 2.1	18.5 ± 2.1	0.2 ± 2.8 (2.3 ± 15.4)	0.28	0.78	0.1 [-0.7, 0.9]	-0.9 ± 2.4 (4.5 ± 12.1)	-1.42	0.18	-0.3 [-1.0, 0.5]
	S_2	19.1 ± 2.1	18.4 ± 2.0	-0.7 ± 3.3 (2.3 ± 17.2)	-0.78	0.45	-0.3 [-1.1, 0.5]				
PA_{DIST} (°)	S_1	22.3 ± 2.4	21.8 ± 4.0	-0.6 ± 2.8 (2.7 ± 11.7)	-0.74	0.47	-0.2 [-0.9, 0.6]	-0.8 ± 3.1 (2.6 ± 13.0)	-0.93	0.37	-0.3 [-1.0, 0.5]
	S_2	22.0 ± 2.7	20.7 ± 2.2	-1.3 ± 2.6 (5.2 ± 10.9)	-1.90	0.08	-0.5 [-1.3, 0.3]				
MT_{MID} (cm)	S_1	2.6 ± 0.4	2.6 ± 0.4	0.0 ± 0.2 (1.1 ± 7.9)	-0.60	0.56	-0.1 [-0.8, 0.7]	-0.0 ± 0.2 (0.3 ± 7.9)	-0.07	0.95	-0.0 [-0.7, 0.8]
	S_2	2.6 ± 0.5	2.6 ± 0.4	0.0 ± 0.1 (0.8 ± 4.2)	-0.91	0.38	-0.1 [-0.8, 0.7]				
MT_{DIST} (cm)	S_1	1.4 ± 0.4	1.4 ± 0.4	-0.1 ± 0.2 (2.8 ± 10.0)	-1.13	0.28	-0.1 [-0.9, 0.7]	0.0 ± 0.2 (0.2 ± 10.7)	0.32	0.75	0.1 [-0.6, 0.8]
	S_2	1.5 ± 0.4	1.4 ± 0.4	-0.1 ± 0.1 (3.0 ± 10.7)	-1.76	0.10	-0.2 [-0.9, 0.6]				
CSA_{MID} (cm^2)	S_1	31.2 ± 6.1	31.2 ± 6.3	0.1 ± 1.2 (0.2 ± 4.4)	0.15	0.88	0.0 [-0.8, 0.8]	0.2 ± 2.0 (0.7 ± 6.9)	0.27	0.79	0.1 [-0.7, 0.9]
	S_2	31.7 ± 6.5	31.9 ± 6.3	0.2 ± 1.2 (0.9 ± 4.3)	0.61	0.56	0.0 [-0.8, 0.9]				
CSA_{DIST} (cm^2)	S_1	10.6 ± 3.2	10.8 ± 3.3	0.2 ± 0.6 (2.3 ± 6.0)	1.23	0.24	0.1 [-0.8, 0.9]	0.1 ± 0.6 (0.8 ± 4.9)	0.46	0.65	0.1 [-0.7, 0.9]
	S_2	10.9 ± 3.2	11.2 ± 3.3	0.3 ± 0.8 (3.1 ± 8.2)	1.22	0.25	0.1 [-0.7, 0.9]				

Table 7.3.3. Between-session comparisons in PRE- and POST-exercise measurements of isometric strength and vertical jump performance.

Variable	S_1 vs. S_2	$\bar{x}_{diff}$ ± SD	95% CI	$\bar{x}_{diff}$ (%)	TE (%)	t	*p*	*g* [95% CI]
ISO_{90} (N)	PRE	7 ± 191	[-92, 107]	0.3	5.4	0.14	0.89	0.0 [-0.7, 0.8]
	POST	47 ± 178	[-45, 140]	2.2		1.00	0.33	0.1 [-0.6, 0.9]
ISO_{120} (N)	PRE	-13 ± 419	[-232, 207]	0.3	6.1	-0.11	0.91	0.0 [-0.7, 0.7]
	POST	227 ± 562	[-67, 521]	5.7		1.51	0.16	0.2 [-0.5, 0.9]
CMJ_F (N)	PRE	25 ± 58	[-8, 57]	1.3	2.0	1.50	0.16	0.1 [-0.7, 0.9]
	POST	9 ± 69	[-30, 49]	0.5		0.46	0.65	0.0 [-0.8, 0.8]
CMJ_H (m)	PRE	0.00 ± 0.04	[-0.02, 0.02]	0.0	6.1	0.07	0.95	0.0 [-0.8, 0.8]
	POST	0.00 ± 0.04	[-0.02, 0.02]	1.0		0.38	0.71	0.0 [-0.7, 0.8]
CMJ_V (m/s)	PRE	0.00 ± 0.14	[-0.08, 0.07]	0.1	3.3	-0.02	0.98	0.0 [-0.8, 0.8]
	POST	-0.01 ± 0.12	[-0.05, 0.07]	0.4		0.31	0.76	0.0 [-0.7, 0.8]
SJ_F (N)	PRE	103 ± 182	[0, 205]	4.8	5.9	2.04	0.07	0.3 [-0.5, 1.1]
	POST	71 ± 229	[-58, 201]	3.5		1.12	0.29	0.3 [-0.5, 1.0]
SJ_H (m)	PRE	0.00 ± 0.04	[-0.02, 0.02]	0.7	7.9	-0.30	0.77	0.0 [-0.8, 0.7]
	POST	0.00 ± 0.03	[-0.01, 0.02]	1.3		0.49	0.63	0.1 [-0.7, 0.8]
SJ_V (m/s)	PRE	0.02 ± 0.15	[-0.09, 0.06]	0.7	4.2	-0.40	0.70	0.0 [-0.8, 0.7]
	POST	-0.02 ± 0.13	[-0.05, 0.09]	0.7		0.43	0.68	0.0 [-0.7, 0.8]

Table 7.3.4. Between-session comparisons in PRE- and POST-exercise measurements of the architecture and morphology of the VL muscle.

Variable	S_1 vs. S_2	$\bar{x}_{diff}$ ± SD	95% CI	$\bar{x}_{diff}$ (%)	TE (%)	t	*p*	*g* [95% CI]
FL_{MID} (cm)	PRE	-0.1 ± 0.4	[-0.3, 0.2]	0.8	3.8	-0.54	0.60	0.0 [-0.8, 0.7]
	POST	0.1 ± 0.4	[-0.1, 0.3]	1.5		1.23	0.24	0.1 [-0.6, 0.9]
FL_{DIST} (cm)	PRE	0.2 ± 0.6	[-0.1, 0.6]	2.4	4.3	1.50	0.16	0.1 [-0.6, 0.9]
	POST	0.1 ± 1.1	[-0.5, 0.7]	0.6		0.23	0.82	0.0 [-0.7, 0.8]
PA_{MID} (°)	PRE	0.8 ± 1.8	[-0.2, 1.8]	4.3	7.0	1.60	0.14	0.4 [-0.4, 1.1]
	POST	-0.1 ± 1.3	[-0.8, 0.6]	0.6		-0.33	0.75	-0.1 [-0.8, 0.7]
PA_{DIST} (°)	PRE	-0.3 ± 2.3	[-1.5, 0.9]	1.3	7.3	-0.48	0.64	-0.1 [-0.9, 0.6]
	POST	-1.1 ± 3.0	[-2.7, 0.5]	4.9		-1.32	0.21	-0.3 [-1.1, 0.4]
MT_{MID} (cm)	PRE	0.0 ± 0.2	[-0.1, 0.1]	1.6	5.6	0.73	0.48	0.1 [-0.6, 0.8]
	POST	0.0 ± 0.2	[0.0, 0.1]	1.7		1.13	0.28	0.1 [-0.6, 0.8]
MT_{DIST} (cm)	PRE	0.0 ± 0.2	[-0.1, 0.1]	1.3	10.4	0.34	0.74	0.0 [-0.7, 0.8]
	POST	0.0 ± 0.2	[-0.1, 0.1]	0.5		0.13	0.90	0.0 [-0.7, 0.8]
CSA_{MID} (cm^2)	PRE	0.5 ± 1.2	[-0.1, 1.2]	1.7	2.8	1.44	0.18	0.1 [-0.7, 0.9]
	POST	0.7 ± 1.3	[0.0, 1.4]	2.2		1.78	0.10	0.1 [-0.7, 0.9]
CSA_{DIST} (cm^2)	PRE	0.3 ± 0.8	[-0.1, 0.7]	3.1	5.1	1.48	0.17	0.1 [-0.7, 0.9]
	POST	0.4 ± 0.9	[-0.1, 0.9]	3.8		1.56	0.15	0.1 [-0.7, 0.9]

Table 7.3.5. Between-session comparisons in PRE- and POST-exercise measurements of the contractile properties of the VL muscle.

Variable	S_1 vs. S_2	$\bar{x}_{diff}$ ± SD	95% CI	$\bar{x}_{diff}$ (%)	TE (%)	t	*p*	*g* [95% CI]
T_d (ms)	PRE	-0.4 ± 1.4	[-1.1, 0.3]	1.7	4.2	-1.06	0.31	-0.3 [-1.1, 0.4]
	POST	0.4 ± 1.4	[-0.4, 1.2]	1.8		1.02	0.33	0.2 [-0.5, 1.0]
D_m (mm)	PRE	-0.1 ± 1.2	[-0.7, 0.6]	1.0	15.9	-0.18	0.86	0.0 [-0.8, 0.7]
	POST	-0.1 ± 0.6	[-0.4, 0.2]	2.2		-0.61	0.55	0.0 [-0.8, 0.7]
V_c (mm/ms)	PRE	0.00 ± 0.02	[-0.01, 0.01]	0.3	15.2	0.22	0.83	0.0 [-0.7, 0.7]
	POST	0.00 ± 0.02	[-0.01, 0.01]	13.9		-0.60	0.56	0.0 [-0.7, 0.7]

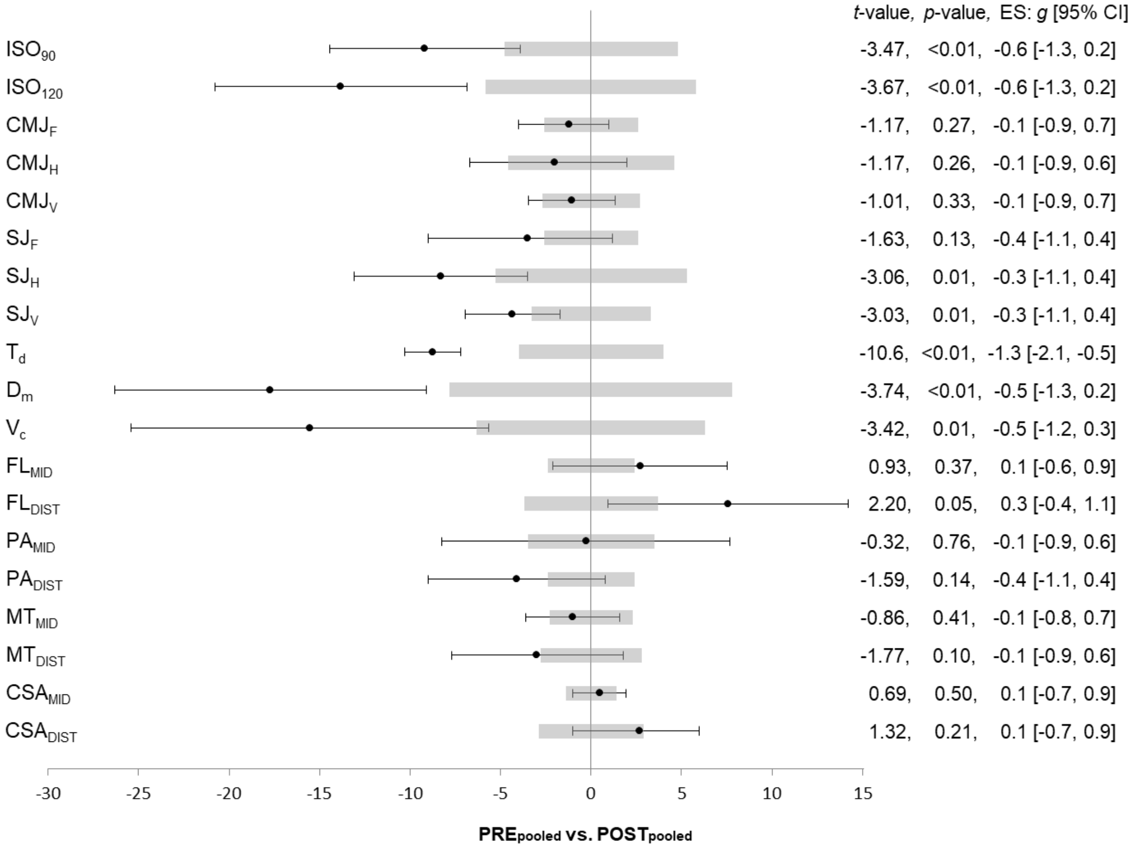

Figure 7.3.1. Relative changes in isometric strength, vertical jump performance, VL muscle contractile properties, VL muscle architecture and VL muscle morphology following eccentric exercise. Solid circles denote the group mean values. Error bars represent 95% CI. Light grey bars denote the typical error associated with each measurement. The left side of the graph lists the dependent variables. The right side of the graph displays the t-value, p-value and Hedges g effect sizes [95% CI] associated with each variable.

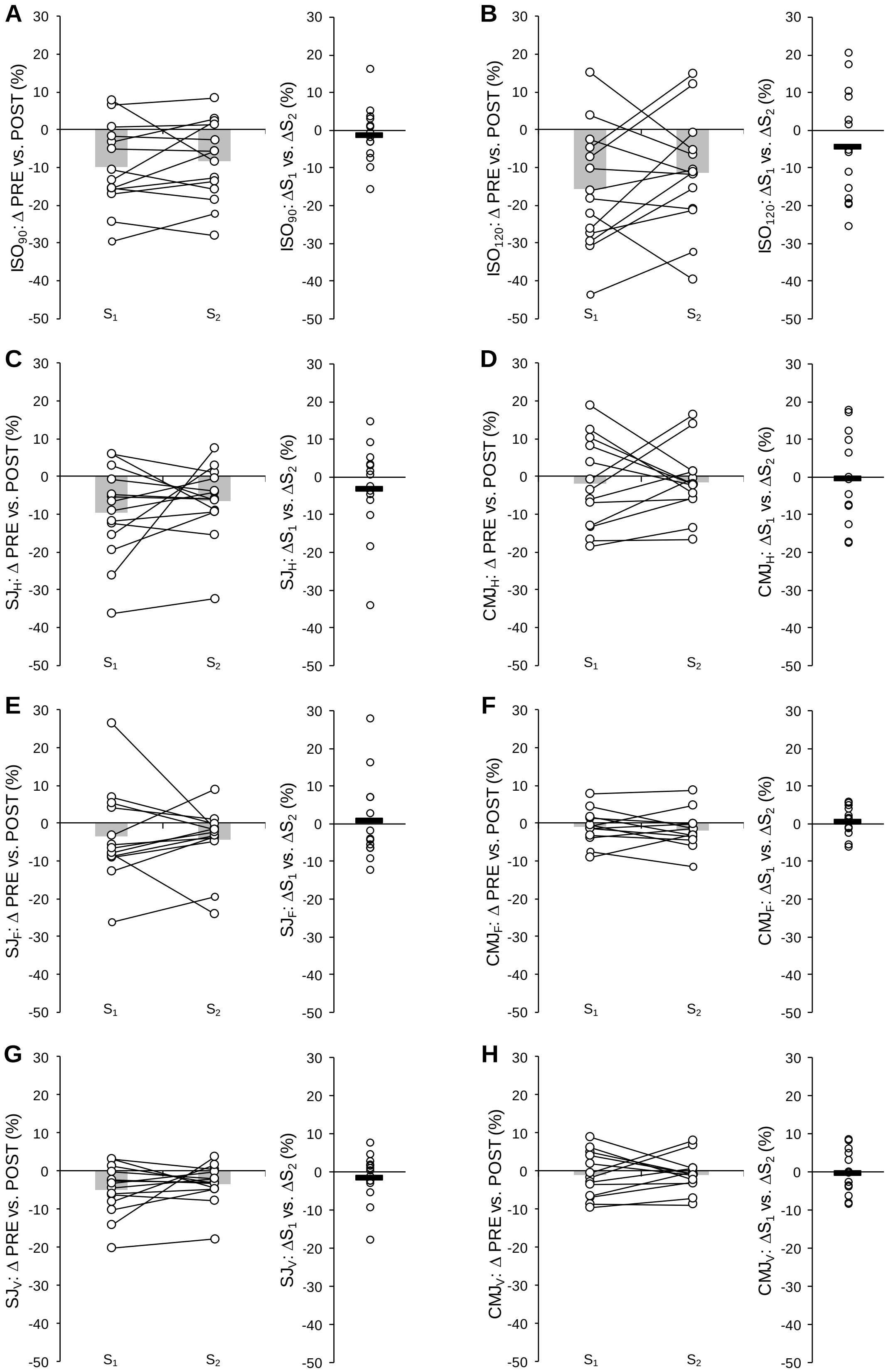

Figure 7.3.2. Paired-data scatterplots showing individual differences within- and between-sessions, and the magnitude of within-session change between-sessions for aspects of performance. Grey bars represent group mean values.

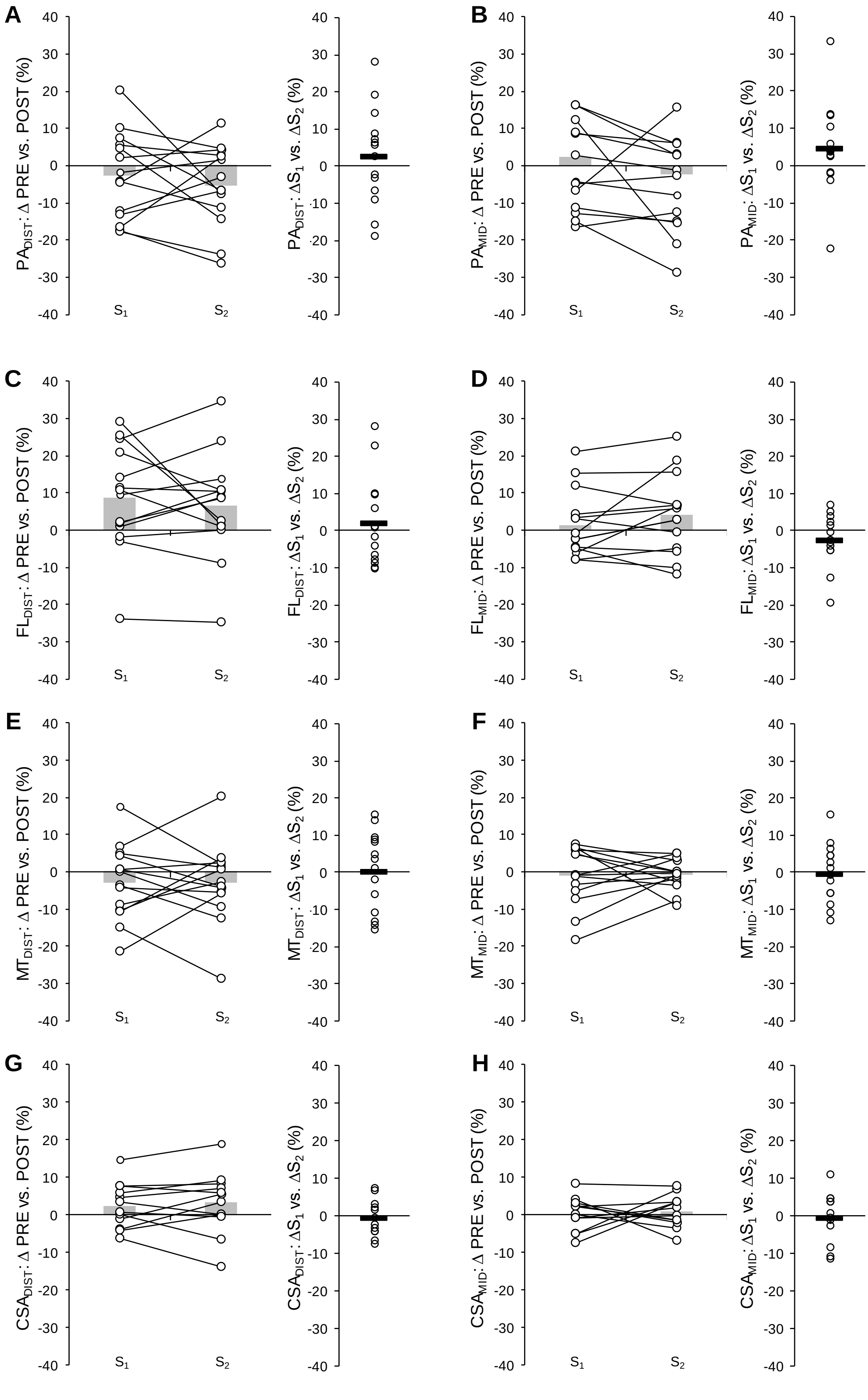

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Figure 7.3.3 Paired-data scatterplots showing individual differences within- and between-sessions, and the magnitude of within-session change between-sessions for VL muscle architecture and morphology. Grey bars represent group mean values.

7.4 Discussion

The overarching aim of this investigation was to gain an insight into the immediate exercise-induced alteration in muscle function and muscle ultrastructure following an initial and repeated bout of high-intensity eccentric resistance exercise. The results indicate that performing high-intensity eccentric exercise reduced isometric strength at full and partial ROM and had a negative effect on SJ performance resulting from reduced force producing capacity and movement velocity. However, peak force and velocity characteristics during the concentric phase of the CMJ jump were not notably affected, and therefore CMJ performance was not markedly impaired. The exercise typically increased stiffness and impaired muscle contractile velocity of the VL muscle, concurrent with increased FL_{DIST} and slight decreased MT_{DIST}. There were subtle indications that the repeated bout of exercise resulted in marginally augmented responses in FL_{MID} and PA_{DIST} and marginally attenuated responses in ISO_{120} and T_d. Though importantly, underpinning these data were highly varied profiles of individual responses. Due to this, the group data does not necessarily offer an accurate reflection of the responses demonstrated by several participants.

It is common for eccentric resistance exercise to reduce maximal voluntary force output (Clarkson *et al*., 1992; Howatson *et al*., 2007; Hunter *et al*., 2012; Souron *et al*., 2018). Force reduction has been attributed to; impaired peripheral function and perturbation to the excitation-contraction coupling mechanisms (Hyldahl and Hubal, 2014) and the inability to attain pre-exercise levels of muscle activation (Prasartwuth *et al*., 2005). Although these data cannot provide clear insight into the latter it can provide some insight into the peripheral mechanisms which altered simultaneously with impaired maximal voluntary force output and therefore could explain some of the reduction in force output.

Hunter *et al.* (2012) and Macgregor *et al.* (2016) suggested that altered muscle contractile characteristics measured using TMG, similar in nature to those observed in the present study, were representative of an increase in muscle stiffness. Although the increased stiffness and thus, reduced muscle laxity, would lead to a more timely response from the muscle and a more efficient transfer of force produced by muscle contraction through to tendon (Wilson *et al*., 1994), the response may not provide a performance benefit if force producing capacity is compromised. Muscle stiffness in conjunction with impaired muscle function has been attributed to impaired excitation-contraction coupling and altered calcium mechanics resulting from structural disruption to the sarcomeres (Warren *et al*., 2001). Theoretically, the repercussions of such disruption would slow down action potential propagation and muscle fibre conduction velocity, hence impede muscle contractile velocity (Macgregor *et al*., 2016). Therefore, it appears that a response characterised by an increase in muscle stiffness and reduced contractile velocity, similar to that observed in the present study, could signify a degree of EIMD. Although, when considering the magnitude of the reduction in voluntary force output taken immediately following exercise, it is less than that reported in the body of EIMD research (Michaut *et al*., 2001; Nosaka and Newton, 2002; Prasartwuth *et al*., 2005; Sayers *et al*., 2003; Souron *et al*., 2018). Therefore, it could be assumed that the supposed degree of EIMD may not be excessive and the impaired response is, instead, indicative that the protocol could be effective in eliciting an adaptive response if used habitually. Unfortunately, it is unknown whether the magnitude of these response may be exacerbated, or diminished, in the hours and days following the exercise bout as this was not measured.

Typically, measures of PA, MT and CSA following eccentric exercise are used as a means to detect exercise induced muscle swelling, which is typically caused by inflammatory response or vascular perfusion (Chleboun *et al*., 1998; Yu *et al*., 2015). These data do not clearly indicate a muscle swelling response. However, given that the present study is limited to the response that falls within 60 minutes of completing the exercise bout this response could have been missed given that numerous other sources have reported alterations in these parameter in the hours and days following the exercise bout (Chleboun *et al*., 1998; Howatson *et al*., 2007; Ishikawa *et al*., 2006; Yu *et al*., 2015).

The alteration in measurements of muscle architecture and morphology were similar to those presented by Ishikawa *et al.* (2006). These authors observed an increase in FL, decrease in PA and no definitive alteration in MT in the soleus muscle shortly following repetitive exercise utilising the SSC. Conversely, an increase in PA and MT were observed following exhaustive cycling exercise (Brancaccio *et al*., 2008) and fatiguing isometric exercise of the knee extensors (Kubo *et al*., 2001). Unlike these studies, Csapo *et al.* (2011) captured measurements of FL; the investigators observed a decrease in FL alongside an increase in PA and MT following exhaustive leg press exercise. It appears that exercise which emphasises the intensity of the eccentric muscle action could result in a stretch-mediated response in muscle architectural characteristics.

Increased FL implies increased serial compliance of the VL muscle which can perhaps be the effects of regions of lengthened half-sarcomeres and/or series elastic structures (Saxton and Donnelly, 1996). Nonetheless, an assumption could be made that that the other muscles (vastus medialis, vastus intermedialis, RF and gluteal musculature) which are likely to have been subject to lengthening action during the prescribed exercise could have also undergone a subtle increase in muscle length. If this is the case, the optimum operating length could have become longer and shifting the muscles length-tension relationship (Ishikawa *et al*., 2006; Philippou *et al*., 2009; Proske and Morgan, 2001). Shifting the length-tension relationship in the knee and hip extensor musculature could account for the subtle disparity in the decline of maximum isometric force output between knee joint angles after exercise.

Despite impairment to aspects of neuromuscular function following eccentric exercise, CMJ performance was preserved. It is not uncommon for CMJ to be used to monitor neuromuscular function (Gathercole *et al*., 2015). The functional impairments brought about by the prescribed exercise could have been offset by the inclusion of an active pre-stretch prior to the propulsive phase which facilitates; the time available to develop force, the active state at the start of the propulsive phase, storage and utilisation of elastic energy from series and parallel components, contractile potentiation and reflex contribution (Van Ingen Schenau *et al*., 1997). Alternatively, it is possible that jump strategy may have been momentarily altered and a more effective strategy adopted to preserve overall performance. There are several variables that could have been captured that relate to CMJ mechanics which, unfortunately, were not captured in this investigation. This information would have provided a greater insight into how the CMJ may be affected after undertaking eccentric exercise. Nonetheless, this is insightful for practitioners when planning multi-session training days, as it could be appropriate to organise tasks involving the SSC after an eccentric training stimulus.

There were subtle indications that the repeated bout of exercise resulted in augmented FL_{MID} and PA_{DIST} which were not detected following the initial bout.

Additionally, the impaired responses in ISO_{120} and T_d were attenuated following the repeated bout. Intuitively, one would expect diminished magnitude of responses across all variables given that neural, mechanical and cellular adaptations that have been associated with the *repeated bout effect* (McHugh, 2003). However, in the current context one must consider that non-naïve resistance trained individuals may be less susceptible to eccentric exercise-induced impairment (Nosaka and Aoki, 2011) and, as mentioned previously, the magnitude of impairment in the present study was less than that imposed in traditional EIMD research. It could be assumed that the response of ISO_{120} may reflect neural adaptation and T_d may reflect mechanical adaptation. Although, this cannot be attributable to alterations of muscle architectural characteristics, given that the response was similar or exaggerated following the repeated bout. Importantly, given that the *repeated bout effect* considers the hours and days after exercise the present investigation has overlooked an important component of this phenomena. Notwithstanding, from a practical perspective this information could assist with the organisation of a similar stimulus in the training schedule.

Whilst the group data brings valuable information, it is important for readers to interpret these data with caution and have an appreciation for the highly varied individual profiles that underpin these data (Figure 7.3.2 and Figure 7.3.3). Consequently, a number of the individual responses may well deviate from the characteristic profiles that have been presented and discussed. Variation in physiological responses can occurs due to a myriad of factors, including an individual's genotype, phenotype, training status and nutritional intake alongside with physical training (Swinton *et al*., 2018). Individual variations in response to eccentric exercise has been attributed to genetic factors; the ACTN3 gene could increase an individual's tolerance to eccentric exercise (Pickering and Kiely, 2017). Furthermore, individuals who have performed habitual concentric exercise are likely to be susceptible to, or exacerbate signs of muscle damage and/or muscle functional impairment in response to eccentric exercise (Whitehead *et al*., 1998). This could be due to muscle fibres settling at a shorter optimum length, increasing their susceptibility to damage when undergoing lengthening action (Brockett *et al*., 2002). Considering the above information and given the different mechanisms underpinning muscle force generation, it is likely that the discrepancy in muscle force output expressed during isometric versus eccentric exercise is likely to be disproportionate across individuals. If this is the case then during the prescribed exercise, the individuals would have been working at different intensities relative to their eccentric strength which would have exacerbated to the varied responses. Considering this, although isometric force output has provided a successful platform to prescribe eccentric training loads, it may not be the most optimal platform.

Overall, this investigation has offered an awareness of the immediate training-induced effects of high-intensity, multi-joint eccentric exercise which included; impaired force producing capacity and SJ performance, and altered VL muscle contractile characteristics and muscle architecture predominantly in the distal region of the VL muscle. Interestingly, CMJ performance was not affected. It was clear that individual responses to the initial and repeated bout of exercise varied in nature and magnitude. For this reason, when prescribing high-intensity eccentric exercise an individualised approach is advised. Overall, the information derived from this investigation has indicated the training adaptations that could be expected from habitual use of high-intensity eccentric exercise. Although it did not capture the time-course of recovery, it has provided some useful information to assist in estimating the time needed for recovery to type of stimulus and informing the overall organisation and management of the training stimulus (or similar) within a broader performance programme.

7.5 Applied Perspective

The overarching aim of this investigation was to gain an insight into the immediate exercise-induced alteration in muscle function and muscle ultrastructure following an initial and repeated bout of high-intensity eccentric resistance exercise. This specifically addresses the fifth aim of this thesis. This investigation characterised the nature and magnitude of neuromuscular and morphological alteration to high-intensity eccentric exercise in trained individuals using pre-determined measurement sensitivity thresholds. It has highlighted those characteristics that are most susceptible to eccentric loading and provided an indication about the adaptations that may arise following chronic training (which will be addressed in Chapter 9). Importantly, the information gives an idea of individual tolerances to this type of exercise. Although the group data may not suggest a significant impact to physical performance and the investigation did not monitor the time-course of recovery, based on anecdotal evidence some of the ‘high-responders’ verbalised that they needed numerous days to recover and the exercise bouts impeded their desire to participate in physical exertion. Considering this, it may be more appropriate to consider implementing a lower volume of high-intensity eccentric exercise with athletes who are required to train numerous times per week. This was considered for the prescription of the training programme featured in Chapter 9. Prior to the investigation comprising Chapter 9, however, this study prompted investigation into developing a more definitive evaluation of eccentric strength which could form a more accurate platform to prescribe individualised eccentric training programmes (Chapter 8). This was based on the premise that the discrepancy in isometric versus eccentric strength may be disproportionate across individuals, which would exacerbate individual responses to eccentric exercise when training load is prescribed based on isometric strength.

Chapter 8

Repeatability and Specificity of Eccentric Force Output and the Implications for Eccentric Training Load Prescription

8.1 Introduction

It is common practice for S&C practitioners, rehabilitation professionals and sports science researchers to prescribe supramaximal eccentric loads and/or evaluate eccentric performance grounded on RM strength tests which are based on strength during the lifting phase (Barstow *et al*., 2003a; Ben-Sira *et al*., 1995; Brandenburg and Docherty, 2002; Doan *et al*., 2002; English *et al*., 2014a; Friedmann-Bette *et al*., 2010b; Moir *et al*., 2013). This approach to load prescription overlooks task-specificity and the possibility that some individuals have a different tolerance for eccentric exercise (Pickering and Kiely, 2017). As such, prescribing resistance exercise based on non-specific measures of strength could result in the athlete working at sub-optimal intensities (either too high or too low). This is likely to decrease the efficacy of eccentric training regimes and impede functional evaluations of the neuromuscular responses to eccentric exercise. Ensuring that exercise prescription is accurate will not only enhance the effectiveness of eccentric resistance training regimes, but it will reduce the risk of injury and prevent excessive training load. This is especially important in a high-performance context, when eccentric training loads are likely to be extremely high.

In order to inform the prescription of eccentric training loads and evaluation of muscle function under high-intensity eccentric conditions, this study implemented a test battery that included ECC_{1RM}, $TRAD_{1RM}$, ISO_{90} and ISO_{120} with the aim to determine the repeatability and specificity of eccentric force output and assess the methodological accuracy when using non-specific measures of strength to prescribe eccentric training loads. This specifically addresses the sixth aim of this thesis. We hypothesised that force output would be task-specific, and force profiles would demonstrate inter-subject variability. Consequently, approaches that use non-specific measures of strength to prescribe eccentric load would be associated with a degree of inaccuracy.

8.2 Methods

8.2.1 Experimental Approach

A within-subjects, repeated measures design was used to determine the repeatability and specificity of force output during ECC_{1RM} compared to $TRAD_{1RM}$, ISO_{90} and ISO_{120} during a lower body, multi-joint exercise performed on a leg press device. Participants attended the facility on three separate occasions, separated by seven days. Following familiarisation of the testing procedures during the first visit, strength assessments were performed during visit two and were repeated during visit three. Maximal force output during ISO_{90} and ISO_{120} was assessed within three efforts, for each task, whereas $TRAD_{1RM}$ and ECC_{1RM} were assessed within five and six efforts, respectively. Testing for each muscle action was separated by 10 minutes to allow sufficient recovery. The assessments were purposely performed in the following order; (1) ISO_{90}, (2) ISO_{120}, (3) $TRAD_{1RM}$, and (4) ECC_{1RM} to ensure some level of incremental preparation was delivered in preparation for increasing loads.

8.2.2 Participants

Twelve strength-trained males (mean ± SD age, stature and body mass: 31 ± 6 years, 181.8 ± 3.6 cm and 87.6 ±7.9 kg, respectively) volunteered to participate in this study. Participants had 12 ± 9 years of resistance training experience and had a strength-power sport background e.g. rugby, combat, powerlifting, track and field. Details of participant injury history, pre-test requirements, testing procedures and ethical approval details are consistent with those outlined in section 5.2.2.

8.2.3 Strength Profile

Assessment was conducted following the general warm-up which was conducted according to the procedures outlined in section 5.2.3.

Isometric Force Assessment. The procedures for assessing ISO_{90} and ISO_{120}, and rationale for the choice of joint angles are outlined in section 5.2.4. Repeatability of measurements using these methods are detailed in Chapter 5 (see Table 5.3.1).

$TRAD_{1RM}$ Assessment. This assessment determined the maximum weight that could be moved through an initial lowering (eccentric) then lifting (concentric) phase to the nearest 5 kg for a single repetition. This was established within five attempts, each effort separated by five minutes. The speed of the preceding eccentric descent was self-selected by the participant. However, the ROM was standardised to 90° of knee flexion (verified using an auditory signal offered by the leg press device technology). If full ROM was not achieved, then the effort was deemed a failed repetition and the effort was repeated after five minutes. The force data taken for analysis reflected the force imposed by the external load and not the propulsive force corresponding to how the load is being moved. Importantly, this approach ensured practicality of the findings such that they can be interpreted by practitioners who do not have access to force plates on a similar device.

ECC_{1RM} Assessment. This assessment determined the maximum force that could be imposed on the participant which could be controlled throughout the ROM of the descending phase of the leg press exercise for a duration of five seconds and following a concentric phase loaded with 50% $TRAD_{1RM}$. The loading parameters for the concentric phase differed from previous experimental studies (Chapter 6 and 7) where 1.5 times bodyweight was used. In the present study, a measure of $TRAD_{1RM}$ was being attained as part of the testing procedures therefore acquiring

this information did not require any additional testing. Despite the differences, both methods are still considered relatively low intensity.

To standardise the pace of the eccentric phase, a custom-built LED strip with individually addressable LEDs (WS2812, BTF Lighting Technology Co. Ltd) controlled by a development board (Elegoo Mega 2560 R3, Elegoo Inc. UK & Arduino 1.8.4) and custom written code was added to the instrument. The LEDs light up in a gradual manner to create a light trail that the participant followed, using a marker that is secured to the foot carriage (Figure 8.2.1). The length of the light trail (total number of LED lights) is pre-set to a distance that reflects the displacement that the foot carriage has to travel until the participants knee reaches 90° angle. The first ECC_{1RM} effort was performed with a load which was equivalent to $TRAD_{1RM}$, which had been established in the previous assessment. Upon successful completion of an effort, intensity was increased by 5% until the five seconds pace set by the LED lights could no longer be maintained. Inability to maintain the required TUT was deemed a failure. Following a failed effort subjects were given five minutes to rest before attempting the load once more. In the event of a second failed attempt, force output associated with the preceding effort was used for analysis. Maximum was achieved within six efforts, each separated by five minutes.

Figure 8.2.1. ECC_{1RM} pacing tool.

8.2.4 Data Analysis

The procedures for checking data prior to analysis and calculating reproducibility of measurements are outlined in section 5.2.5. Data from each session were pooled and a repeated measures ANOVA, followed by a Bonferroni *post-hoc* test was used to investigate differences in force output when comparing ECC_{1RM} to ISO_{90}, ISO_{120} and $TRAD_{1RM}$. ECC_{1RM} force output data was normalised to $TRAD_{1RM}$, ISO_{90} and ISO_{120} and expressed as a percentage. Pearson's correlation (*r*) and linear regression analysis were used to evaluate the strength of the relationships between ECC_{1RM} force output and $TRAD_{1RM}$, ISO_{90} and ISO_{120} force output and obtain equations used to estimate ECC_{1RM} force output. Residuals analysis was used to determine the absolute differences in observed and estimated ECC_{1RM} values for each data set to highlight measurement bias ($\bar{x}_{diff}$) and precision of the estimation (95% CI). To measure the accuracy of the predictions the standard error of the estimate (SEE) was calculated using the following formula:

$$SEE = \sqrt{\frac{\sum(Y - Y')^2}{N}}$$

Where, Y – Y' is the difference between the actual and predicted scores. A paired samples t-test was used to determine differences between observed and estimated ECC_{1RM} values. Effect sizes for ANOVA (η_p^2) and t-tests (*g*) were calculated and interpreted in accordance to section 6.2.5 and 7.2.8, respectively.

8.3 Results

Test-retest measurements were not significantly different ($p > 0.05$, $g < 0.2$). Reliability of the test battery was established (ICC > 0.95; CV < 6%; Table 8.3.1). Differences in force output between tasks were significant ($F_{3, 70} = 102.6$, $p < 0.001$, $\eta_p^2 = 0.8$). Force output for ECC_{1RM}: 4034 ± 592 N (95% CI: 3658, 4410 N) was greater ($p < 0.001$) than ISO_{90}: 3122 ± 579 N (95% CI: 2755, 3490 N) and $TRAD_{1RM}$: 3574 ± 581 N (95% CI: 3204, 3943 N), but significantly less ($p < 0.001$) than ISO_{120}: 6285 ± 1546 N (95% CI: 5302, 7267 N). When normalised, ECC_{1RM} equated to; 113 ± 6% (95% CI: 109, 117%), 130 ± 12% (95% CI: 123, 138%) and 67 ± 14% (95% CI: 58, 76%) of $TRAD_{1RM}$, ISO_{90} and ISO_{120}, respectively. These percentage differences were not consistent between individuals (Figure 8.3.1). There was a strong linear relationship between; ECC_{1RM} and ISO_{90} (r = 0.88, p < 0.01) and, ECC_{1RM} and $TRAD_{1RM}$ (r = 0.93, p = 0.00). There was a moderate linear relationship between ECC_{1RM} and ISO_{120} (r = 0.43, p < 0.01). The equations for predicting ECC_{1RM} from: ISO_{90}: $0.90x + 1212.37$, $TRAD_{1RM}$: $0.95x + 632.42$ and $ISO_{120} = 0.17x + 2996.40$. Using these prediction equations, the $\bar{x}_{diff}$ between observed and estimated ECC_{1RM} force outputs were not statistically significantly different (p > 0.99; g = 0.0); ISO_{90}: -1.0 ± 277.3 N (95% CI: -157.9, 155.9 N, SEE: 266 N); $TRAD_{1RM}$: 0.1 ± 211 N (95% CI: -119.4, 119.6 N, SEE: 202 N) and ISO_{120}: -0.01 ± 534.4 N (95% CI: -302.4, 302.3 N, SEE: 512 N). Residual plots are presented in Figure 8.3.2.

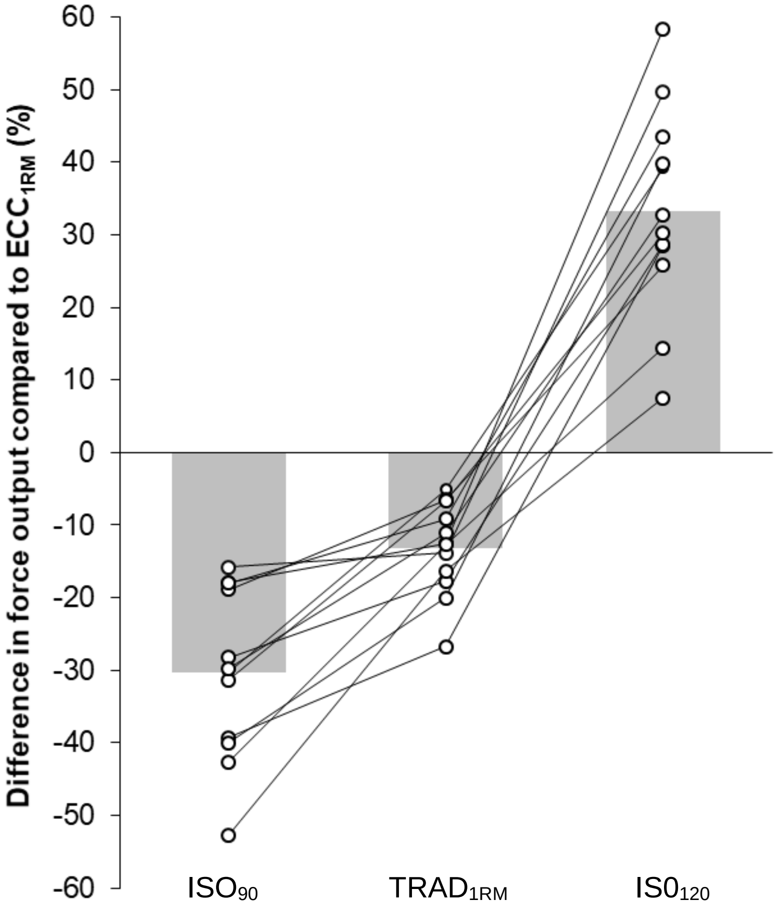

Figure 8.3.1. Representation of the percentage difference in force output between ECC_{1RM} and; ISO_{90}, $TRAD_{1RM}$ and $IS0_{120}$ for each participant. Grey bars represent the mean difference compared to ECC_{1RM}.

Table 8.3.1. Between-session reproducibility of the strength profile.

		Av. Force (N)								
Trial	Session No.	$\bar{x}$ ± SD	95% CI	*p*	*g*	TE (%)	SWC (%)	CV (%)	ICC
ISO_{90}	1	3171 ± 624	(2775, 3568)	0.06	0.17	2.4	3.4	3.8 (2.6, 6.5)	0.97 (0.90, 0.99)
	2	3073 ± 542	(2729, 3418)						
$TRAD_{1RM}$	1	3604 ± 628	(3205, 4003)	0.13	0.10	1.6	2.2	2.5 (1.8, 4.4)	0.98 (0.93, 0.99)
	2	3544 ± 538	(3202, 3886)						
ECC_{1RM}	1	4088 ± 642	(3680, 4496)	0.12	0.18	4.1	3.0	3.8 (2.7, 6.6)	0.95 (0.84, 0.99)
	2	3980 ± 560	(3624, 4336)						
ISO_{120}	1	6400 ± 1587	(5391, 7408)	0.20	0.15	3.8	5.0	5.8 (4.1, 10.0)	0.96 (0.87, 0.99)
	2	6170 ± 1560	(5179, 7162)						

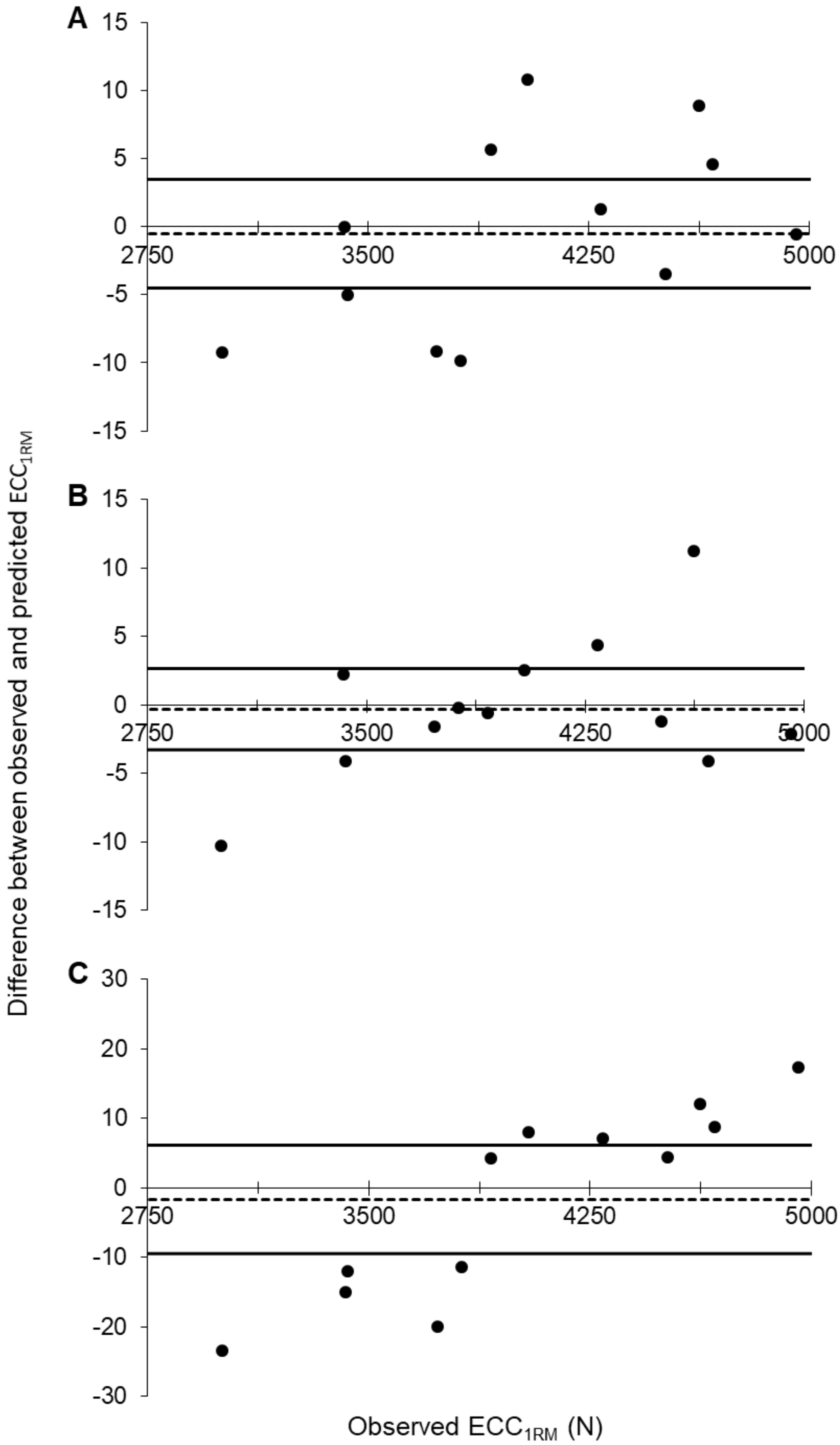

Figure 8.3.2. Absolute differences in observed and estimated ECC_{1RM} force output values derived from; (A) ISO_{90}, (B) $TRAD_{1RM}$ and (C) ISO_{120} measures of strength. Dotted line represents calculation bias (mean difference). Solid lines represent calculation precision (95% CI).

8.4 Discussion

The aim of this study was to determine the repeatability and specificity of eccentric force output and assess the methodological accuracy when using non-specific measures of strength to prescribe eccentric training loads. This specifically addressed the sixth aim of this thesis. In summary, this study established that ECC_{1RM} was repeatable, along with performance under the other components of the test battery. Specificity of eccentric force output was demonstrated, as ECC_{1RM} was greater than ISO_{90} and $TRAD_{1RM}$ but less than ISO_{120} due to the different knee joint angle. Participants presented individual tolerances to strength assessment. Hence, estimations of eccentric strength derived from non-specific measures of strength were associated with a margin of error.

A specialised eccentric assessment has been examined and strong evidence has been provided that the method used is reliable. The repeatability of ECC_{1RM} force output from the current study are consistent with previous findings for eccentric strength parameters obtained using isokinetic tasks: ICC: 0.81-0.99 and CV: 4-13% (Bridgeman *et al*., 2015; Farthing and Chilibeck, 2003a; Hortobágyi *et al*., 1996b; Papadopoulos *et al*., 2013; Walker *et al*., 2016)] and isotonic tasks: ICC: 0.79-0.99 and CV: 2-13% (Bogdanis *et al*., 2018; Hollander *et al*., 2007; Sabido *et al*., 2017; Vikne *et al*., 2006). In the current study, the error associated with each strength task was no more than 3% for $TRAD_{1RM}$, 4% for ISO_{90} and ECC_{1RM}, and 6% for ISO_{120}. Alongside the SWC and TE, this information proved useful when interpreting performance changes following the training intervention comprising Chapter 9. Importantly, the outcomes of the eccentric assessment were not dissimilar to the other more established components of the test battery. Overall, these data support that task-specific ECC_{1RM} assessment is a reliable means to assess eccentric performance. When incorporated within a more global strength testing battery, attaining a profile of specific strength qualities would serve to highlight the potential training needs of the athlete. However, in the context of the current work, the strength profile enabled the evaluation of the effects of a novel eccentric training prescription on a range of strength qualities (Chapter 9).

The testing battery used in this study enabled the researcher to identify and compare absolute force output associated with different strength qualities during lower body, multi joint exercise. As expected, when matched for ROM, ECC_{1RM} was higher compared to ISO_{90} and $TRAD_{1RM}$, which differed by ~30% and ~13%, respectively. This can be attributed to the unique mechanical and neural features associated with eccentric muscle actions (Enoka, 1996b; Franchi *et al*., 2017; Herzog, 2014) which were discussed in detail in Chapter 2. The magnitude of force enhancement relative to isometric force output is in line with previously established magnitudes (Chapter 5) and with others (Hortobágyi *et al.,* 2001; Reeves and Narici, 2003; Skarabot *et al.,* 2018). However, the magnitude of force enhancement relative to $TRAD_{1RM}$ (~13%) appears modest compared to others (Ben-Sira *et al*., 1995; English *et al*., 2014a; Friedmann-Bette *et al*., 2010b; Hortobágyi *et al*., 1996b; Moore *et al*., 2012b). Yet this could be attributed to the use of constant external resistance, the difference in eccentric tempo, muscle groups used, multi-joint versus isolated movement and the strength level/training status of the participants. Overall, these data support that force output is governed by mode of muscle action.

Conversely, changing the knee joint angle from 90° to 120° resulted in isometric force capacity to exceed ECC_{1RM} force output by a considerable amount (~56%). This concurs with the outcomes of the investigation comprising Chapter 4 and with others (Marcora and Miller, 2000). The heightened force output is attributable to the more mechanically advantageous joint angle (Smidt, 1973). Therefore, it should be considered that when using isotonic exercise, where the magnitude of the load is usually dictated by strength at the end ROM, it is unlikely to match the strength curve of the individual. Hence, greater muscle tension and exercise intensity may be offered by non-eccentric exercise with partial ROM versus high-intensity eccentric exercise at a greater ROM. Practitioners should consider that the higher intensity offered during partial ROM exercise is likely to vary in magnitude for different individuals depending on their strength capacity at a particular joint angle (Figure 8.3.1). At this point, it is not clear to what magnitude ECC_{1RM} would differ from ISO_{90} and/or $TRAD_{1RM}$ under different knee joint-angle constraints, aside from 90° which was employed in the current study.

Participants showed different force generating potential across the different strength tasks. The differences probably reflect the phenotypical expression of neural, biomechanical and morphological adaptations resulting from an individual's training history (Pickering and Kiely, 2017; Zamparo *et al*., 2002).

When considering the performance of all participants the disparity between highest and lowest ECC_{1RM} showed to be as great as 22%, 37% and 51% when normalised to ISO_{90}, $TRAD_{1RM}$ and ISO_{120}, respectively. These data suggest that when using $TRAD_{1RM}$ and ISO measures of strength to prescribe ECC_{1RM} training loads, the prescribed intensity will almost certainly be a mismatch of intended intensity and actual intensity for some individuals because the nature of the prescription method lacks task-specificity.

When investigating this matter further, the current investigation found that despite observing very similar estimated ECC_{1RM} values versus observed ECC_{1RM} data (< 1 N difference in the mean values) when using non-specific measures of strength to estimate eccentric performance, the precision of the estimates was associated with a 3%, 4% and 7% margin of error for $TRAD_{1RM}$, ISO_{90} and ISO_{120}, respectively. When considering the performance of all subjects, the highest underestimations and overestimations were ~10% for ISO_{90}, ~11% for $TRAD_{1RM}$ and ~18% for ISO_{120}. Overestimations in load prescription could increase the propensity of injury or induce overreaching and in extreme cases might add to the risk of overtraining (Bompa and Haff, 2009), especially in a high-performance environment when eccentric loads are likely to be very high indeed. Conversely, underestimations in load prescription result in suboptimal loads and inadequate strength development (Bompa and Haff, 2009). These data provide evidence that using non-specific measures of strength to prescribe ECC_{1RM} training loads is likely to cause errors in predicting eccentric strength that could result in athletes training at an inappropriate intensity to that intended. To ensure accuracy when providing individualised training programmes, it would be prudent to use task-specific assessment for the prescription of training loads and evaluation of muscle function under high-intensity eccentric conditions. Consequently, using a task-specific approach to assess eccentric strength qualities, such as those presented in this study, will provide a more accurate platform to prescribe individualised eccentric training programmes and a more definitive evaluation of eccentric strength.

In this investigation the bespoke leg press device was used to determine the application of strength testing for eccentric overload exercise prescription. Although it is unlikely that practitioners will have this same device in their own training environments, they will almost certainly have inclined leg press devices.

These data provide insight in to how these instruments can be used effectively to gain information on an athlete's capabilities. Critically, this investigation highlights the potential pitfalls of not using task-specific strength testing for eccentric overload training. As a result, testing battery approach of a similar nature to that used in this investigation could be implemented to assess a range of important strength qualities in athletes and to examine progression. These experimental data help inform the prescription and evaluation of muscle function, particularly under high-intensity eccentric conditions using a device and procedures that are translatable to an applied setting. Importantly, the researcher strongly urges S&C practitioners and researchers to consider the development of a direct method to assess maximum eccentric strength qualities to enable accurate, effective and safe performance of high-intensity eccentric exercise.

8.5 Applied Perspective

The aim of this study was to determine the repeatability and specificity of eccentric force output and assess the methodological accuracy when using non-specific measures of strength to prescribe eccentric training loads. This specifically addresses the sixth aim of this thesis. The data derived from this investigation serve to enhance our understanding of the specificity of force output, which is of particular importance when assessing and prescribing eccentric load. The information provided evidence supporting the proposition that individual responses to eccentric loading could be, in part, due to the mismatch of intensity prescription arising from individual variations in eccentric strength versus isometric strength (Chapter 6 and 7). This investigation has revealed that estimating eccentric training loads from strength during non-specific contraction types has the potential to be associated with a high degree of error. From an applied perspective, this has important implications in an applied context whereby it is extremely common to estimate eccentric training loads based on non-specific measures of strength. These results were used to form a more accurate platform to prescribe individualised eccentric training loads and provide a more definitive evaluation of eccentric strength for the training intervention comprising Chapter 9.

Chapter 9

The Application of a Task-Specific Approach to Eccentric Load Prescription and the Effects on Muscle Function, Architecture and Morphology

9.1 Introduction

Muscular strength is considered a major contributing factor to athletic performance (Stone *et al*., 2002). Greater muscular strength is associated with improved force-time characteristics, which translates to enhanced performance across a range of sports skills such as, throwing, jumping, sprinting, and change of direction tasks (Suchomel *et al*., 2016) and is associated with decreased risk of injury (Lauersen *et al*., 2014). Consequently, strength is an important quality for a wide variety of sports, specifically for sports such as Olympic weightlifting, powerlifting and track sprint cycling whereby maximal strength is considered a determinant of performance success. To positively impact an athletes strength, S&C practitioners must prescribe an appropriate and effective training stimulus (DeWeese *et al*., 2015a). Highly trained individuals and elite athletes are more limited in their gains in strength (Baker, 2013; Häkkinen *et al*., 1987), therefore require a novel, high-intensity stimulus to prompt further improvements. The novelty offered by high-intensity eccentric exercise can be considered an appropriate means to increase strength in well-trained individuals and athletes.

Currently, there are few regimes that consider an ecologically valid approaches to training. For this reason, it is difficult for S&C practitioners to translate the processes and outcomes used in scientific research to their practice. A small number of studies have recognised this have provided valuable information to practitioners about the effects of eccentric training in real-world performance scenarios (Cook *et al*., 2013; Dolezal *et al*., 2016; Douglas *et al*., 2018). While these investigations have practically applicability, for this research and a large number of others, the prescription of eccentric training load is based on strength during $TRAD_{1RM}$. As demonstrated in the previous chapter (Chapter 8), the prescription of training load based on an alternate measure of strength has the potential to be inaccurate. Very few authors have acknowledged eccentric specific strength as a means of prescription (Franchi *et al.,* 2014, 2015; Gillies *et al.,* 2006; Housh *et al.,* 1998; Vikne *et al.,* 2006). Those that have, lack aspects of practical applicability to performance contexts through population used, isolated muscle actions, or exercise prescription, for example. To the author's knowledge no investigation has implemented eccentric exercise using isotonic means, with the prescription of training load based on eccentric specific strength and organised in a manner that is consistent with conventional strength training programming and prescription. Furthermore, this approach has not been implemented with strength-trained individuals and athletes.

Using the eccentric strength assessment as a platform for eccentric training load prescription (Chapter 8), the methods that have been developed over the course of this project (Chapter 4-6) and considering the performance questions offered by S&C practitioners (Chapter 3), the aim of this study was to ascertain the feasibility of a strength training programme which incorporates a progressive, task specific approach to eccentric load prescription by; (a) establishing the effects of this approach on muscle function and ultrastructure in well strength-trained individuals and, (b) observing the response of elite sprint cycling athletes when incorporating this approach to strength training alongside sport-specific training. This information contributes towards addressing the seventh aim of this thesis.

9.2 Methods

9.2.1 Experimental Approach

Strength-trained individuals were matched for relative squat 3 RM (SQ_{3RM}) and organised into two groups (STR and TRAD). These participants were strength-trained, but not full-time professional athletes. A group of elite track sprint cycling athletes formed the third group (ATH). All participants performed the same S&C programme for four weeks which consisted of two identical sessions per week. The only variation between the groups was the primary strength exercise which was performed on the bespoke incline leg press. All groups performed this exercise using coupled eccentric-concentric movement with a five seconds tempo for the eccentric phase and explosive action throughout the concentric phase. The difference between the groups was in the loading parameters for the eccentric phase; (1) the TRAD group performed the descending phase with the same load as the ascending phase, which was prescribed based on concentric-only strength (CON_{1RM}), (2) the STR group performed the eccentric and concentric phases with each phase at the same intensity relative to ECC_{1RM} and CON_{1RM} and, (3) the ATH group performed the same as the STR group, but continued with their full-time sport-specific training alongside strength training. The training was preceded by two separate assessment sessions which measured: (1) individual strength profiles (CON_{1RM}, ISO_{90}, $TRAD_{1RM}$ and ECC_{1RM} performed on leg press and SQ_{3RM}), (2) performance during SJ and CMJ, VL CSA, FL, PA and lean leg mass (LLM). Following the 8-session training intervention, all participants took a deload week, which did not include focus on eccentric exercise and instead low volume exercise was performed in the conventional manner by all participants, prior to reassessment of the test battery.

9.2.2 Participants

Seventeen participants, 12 males and five females, volunteered to participate in the study (mean ± SD age, stature and body mass: 24 ± 5 years, 177 ± 9 cm, 79 ± 10 kg, respectively), who were from a strength-power sport background, e.g. Olympic weightlifting, rugby, athletics, gymnastics, combat and track sprint cycling with a between three and 10 years of heavy resistance training experience that incorporated periods of maximum intensity strength training. The characteristics for each training group are summarised in Table 9.2.1. For the duration of the study, the STR and TRAD groups were asked to avoid strenuous resistance training activity and unaccustomed exercise throughout the study duration. The ATH group continued with their on-bike track sprint cycling training programme. Other details pertaining to participant injury history, pre-test requirements, testing procedures and ethical approval details are consistent with those outlined in section 5.2.2.

Table 9.2.1. Participant characteristics at baseline for each training group.

					Strength Profile				
Group	***n***	**Age (yrs)**	**Height (m)**	**BM (kg)**	**ECC_{1RM} ($N \cdot kg^{-1}$)**	**ISO_{90} ($N \cdot kg^{-1}$)**	**CON_{1RM} ($N \cdot kg^{-1}$)**	**$TRAD_{1RM}$ ($N \cdot kg^{-1}$)**	**SQ_{3RM} ($kg \cdot kgBM^{-1}$)**
ATH	5	19 ± 0	174 ± 13	76 ± 12	42.2 ± 7.1	36.8 ± 5.2	36.8 ± 5.0	38.4 ± 4.6	1.6 ± 0.2
STR	6	28 ± 2	179 ± 7	82 ± 9	40.4 ± 5.2	34.5 ± 4.6	34.1 ± 4.5	36.5 ± 3.6	1.7 ± 0.2
TRAD	6	26 ± 5	177 ± 7	77 ± 9	35.7 ± 5.5	33.3 ± 4.9	32.2 ± 4.4	34.7 ± 5.5	1.6 ± 0.3

9.2.3 Muscle Morphology

Measurements of CSA, PA and FL were obtained at 50% (MID) and 25% (DIST) of femur length and 50% of muscle width using the procedures outlined in section 7.2.3. These measurements were used to indicate muscle hypertrophy and the addition of sarcomeres in series and in parallel, as well as to identify regional differences in the muscle response to the exercise intervention (Franchi *et al*., 2014, 2015). Lean leg mass was measured and interpreted using dual-energy X-ray absorptiometry (DXA) in accordance to the procedures outlined in Colyer *et al.* (2016).

9.2.4 Vertical Jump Performance

Measurements of SJ and CMJ were acquired using the equipment and procedures outlined in section 7.2.5. These measurements were implemented into the test battery to serve as an indicator of fatigue post-intervention (as indicated in Chapter 7) to inform the effectiveness of the allocated taper period. Additionally, jump testing was included to assess whether the inclusion of an eccentric training stimulus induces an adaptive response that facilitates performance despite the absence of specific jump training within the training intervention.

9.2.5 Strength Profiling

Individual strength profiles were attained using the equipment and procedures outlined in section 8.2.3. Strength profiles (CON_{1RM}, ISO_{90}, $TRAD_{1RM}$ and ECC_{1RM} performed on leg press and SQ_{3RM}) were attained in accordance to the procedures outlined in section 5.2.4 for $ISO_{90,}$ section 8.2.4 and 8.2.5 for $TRAD_{1RM}$ and ECC_{1RM}, respectively. The strength profile as included to observe the specificity in response to the training intervention. Measurement of SQ_{3RM} was to prescribe the squat exercise protocol, which followed the leg press exercise with the S&C programme. The procedures to attain SQ_{3RM} followed previously established protocol, yielding reproducible results (CV = 2.1%) for strength-trained individuals (Banyard *et al*., 2017). To determine meaningful changes in performance following the training intervention, 2.1% was used as a threshold to detect meaningful change in strength. Briefly, SQ_{3RM} was established in a maximum of five attempts, which did not include the submaximal warm-up repetitions performed up to 85% of predicted 1RM.

9.2.6 Strength & Conditioning Programme

An overview of the S&C programme is shown in Table 9.2.2. The intervention spanned seven weeks in total. Week one and week seven were allocated to baseline and post-testing, respectively. Week two through to week five comprised the main training period. Week six was allocated to a period of deload to offer some recovery and taper prior to performing post-intervention assessment. During the main training period, progressive overload was offered through a gradual increase in intensity (% 1 RM) each week, starting with a range between 82.5 - 87.5% 1 RM in week one to 97.5 - 102.5% 1 RM in week 4. The number of sets and repetitions remained consistent throughout. This was to ensure that adaptive responses to the training intervention could be attributed to the progression of mechanical load and not confounded by fluctuation in training volume offered by the manipulation of sets and repetitions. To the author’s knowledge, this approach to AEL has not be taken previously. The overall aprroach allows for the author to determine the efficacy of prescribing load during the descending phase of a primary strength exercise to the same relative intensity as the ascending phase. Furthermore, this periodisation approach reflects a simple and effective means of developing strength according the high-performance S&C practitioners at the English Institute of Sport. As the programme demanded the development of maximum strength during leg press and squat, concurrently, intensity prescription was the same for both exercises. Accessory exercises followed the key strength exercise, these included a deadlift exercise from the floor which focused on rapid concentric performance and a low load conditioning circuit, including single leg exercise, isometric and a dynamic trunk exercise. To reiterate, the participants performed the same S&C programme, the only difference was in the load prescription for leg press exercise. The STR and ATH groups performed coupled eccentric-concentric leg press exercise with load for the eccentric and concentric phase prescribed relative to ECC_{1RM} and CON_{1RM}, respectively. The TRAD group performed coupled eccentric-concentric leg press exercise with the same load during both phases, which was prescribed relative to CON_{1RM}. The ATH group continued their on-bike track sprint cycling training, which the TRAD and STR groups were not subjected to.

Table 9.2.2. Overview of the S&C programme.

		Training Overview:						
Week #:		WEEK 1	WEEK 2	WEEK 3	WEEK 4	WEEK 5	WEEK 6	WEEK 7
Objectives:		1. Familiarisation 2. Muscle & Strength Assessment	Training 1	Training 2	Training 3	Training 4	Deload	Muscle & Strength Assessment
Intensity Classification:		Very Heavy	Moderate	Moderate-Heavy	Heavy	Very Heavy	Moderate	Very Heavy
Sessions per week:		2	2	2	2	2	2	2
Exercise:		Exercise Prescription: (Sets x reps @ %1 RM):						
1	Leg Press (tempo CON/ECC)	Max	4 x 3 @ 82.5 - 87.5% (X/5)	4 x 3 @ 87.5 - 92.5% (X/5)	4 x 3 @ 92.5 - 97.5% (X/5)	4 x 3 @ 97.5 - 102.5% (X/5)	3 x 3 @ 1.5xBM (X/1)	Max
2	Squat	Max	3 x 3 @ 82.5 - 87.5%	3 x 3 @ 87.5 - 92.5%	3 x 3 @ 92.5 - 97.5%	3 x 3 @ 97.5 - 102.5%	3 x 3 @ 82.5 - 87.5%	Max
3	Explosive Pull From Floor	—	3 x 6 @ 70 - 75%	3 x 6 @ 70 - 75%	3 x 6 @ 70 - 75%	3 x 6 @ 70 - 75%	3 x 3 @ 70%	—
 4a 4b 4c	Low Load Conditioning Circuit: SL Goblet squat Isometric trunk hold Lying leg raise	—	3 rounds: x8 reps x30 s x10 reps	3 rounds: x8 reps x30 s x10 reps	3 rounds: x8 reps x30 s x10 reps	3 rounds: x8 reps x30 s x10 reps	—	—

9.2.7 Data Analysis

All data sets were checked for normality using Shapiro Wilk's test ($p \leq 0.05$). Programme characteristics were examined using a one-way ANOVA to determine the differences in training intensity between the TRAD, STR and ATH groups. To quantify the adaptive response, a repeated measures (PRE vs. POST) ANOVA with between-subjects factor (3 groups; STR, ATH, TRAD) was used to determine main effects of time, main effects of group and group x time interaction in; (1) maximum strength profile, (2) vertical jump performance and (3) VL muscle morphology. The main ANOVA models included η_p^2 effect sizes and were followed by Bonferroni *post-hoc* tests. Relative changes from PRE to POST were presented using forest plots displayed as $\bar{x}$ ± 95% CI. For this aspect of the data, Hedges *g* effect sizes were calculated and interpreted in accordance to section 7.2.8. Thresholds for the TE of the measurements (which were derived from the previous chapters of this work) were used to define practically meaningful changes.

9.3 Results

9.3.1 Programme Characteristics

Relative Training Intensity. Relative training intensity performed during the concentric phase was not statistically significantly different between the three groups ($F_{(2, 21)} = 2.3$, $p = 0.12$, $\eta_p^2 = 0.18$). Relative training intensity performed during the eccentric phase was statistically significantly different between groups ($F_{(2, 21)} = 24.5$, $p < 0.01$, $\eta_p^2 = 0.70$), whereby TRAD trained with lower relative intensity versus STR (-8.42 $N{\cdot}kg^{-1}$ [95% CI: -11.74, -5.09 $N{\cdot}kg^{-1}$]) and ATH (-6.80 $N{\cdot}kg^{-1}$ [95% CI: -10.12, -3.48 $N{\cdot}kg^{-1}$]). Both ATH and STR performed the eccentric phase with 26 ± 4% greater intensity across the training intervention compared to TRAD. An overview of the programme characteristics is shown in Figure 9.3.1. Given that ATH and STR performed the same resistance training programmes at a similar relative intensity these data are summarised in a single graph.

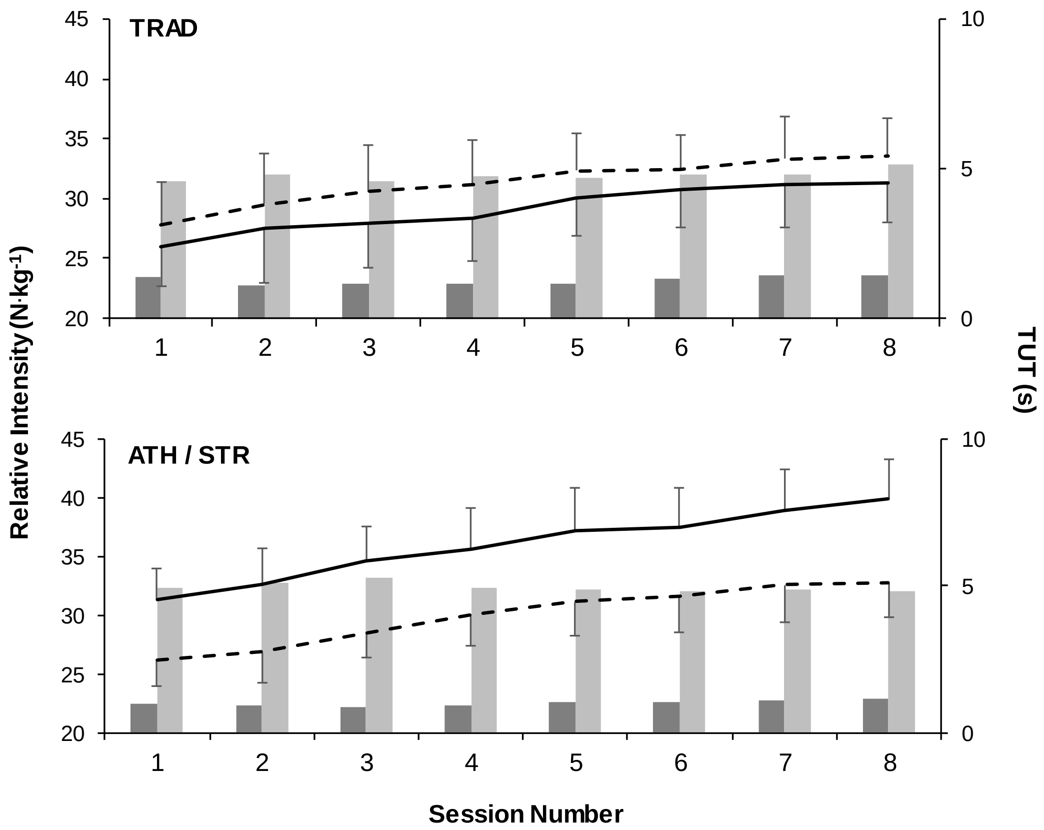

Figure 9.3.1. Training progression over the course of the intervention. The primary axis pertains to relative intensity (presented as $\bar{x} \pm SD$) for the concentric (dashed line) and eccentric (solid line) phase. The secondary axis pertains to TUT for the concentric (dark grey) and eccentric (light grey) phase.

9.3.2 Adaptive Responses

Strength Profile. There were no significant main effects of group for the components of the strength profile (Table 9.3.1). There were significant main effects of time for; ISO_{90}, ECC_{1RM}, CON_{1RM} and SQ_{3RM} (Table 9.3.1). Both STR and TRAD demonstrated statistically significant increase in ISO_{90} (STR: 3.1 N·kg^{-1} [95% CI: 1.4, 4.8 N·kg^{-1}], $p < 0.01$ and TRAD: 1.8 N·kg^{-1} [95% CI: 0.1, 3.5 N·kg^{-1}], $p = 0.04$), whereas ATH tended towards statistically significant increase (ATH: 1.8 N·kg^{-1} [95% CI: -0.1, 3.7 N·kg^{-1}], $p = 0.06$). The relative increase in ISO_{90} exceeded the measurement error for TRAD and STR only (Figure 9.3.3). All groups demonstrated statistically significant increase in ECC_{1RM} (ATH: 2.6 N·kg^{-1} [95% CI: 0.7, 4.5 N·kg^{-1}], $p = 0.01$; STR: 4.1 N·kg^{-1} [95% CI: 2.4, 5.9 N·kg^{-1}], $p < 0.01$ and TRAD: 2.3 N·kg^{-1} [95% CI: 0.5, 4.0 N·kg^{-1}], $p = 0.02$). The relative increase in ECC_{1RM} exceeded the measurement error for all groups (Figure 9.3.3). Both STR and TRAD demonstrated statistically significant improvements in CON_{1RM} (STR: 2.2 $N \cdot kg^{-1}$, [95% CI: 1.0, 3.4 $N \cdot kg^{-1}$], $p < 0.01$ and TRAD: 1.5 $N \cdot kg^{-1}$ [95% CI: 0.3, 2.7 $N \cdot kg^{-1}$], $p = 0.02$), whereas the improvement for the ATH group tended towards statistical significance (ATH: 1.1 $N \cdot kg^{-1}$ [95% CI: -0.2, 2.4 $N \cdot kg^{-1}$], $p = 0.10$). The relative increase in CON_{1RM} exceeded the measurement error for STR only (Figure 9.3.3). All groups demonstrated statistically significant improvements in SQ_{3RM} (ATH: 0.21 BW [95% CI: 0.15, 0.27 BW], $p < 0.01$; STR: 0.08 BW [95% CI: 0.02, 0.13 BW], $p = 0.01$ and TRAD: 0.08 BW [95% CI: 0.02, 0.13 BW], $p = 0.01$). The relative increase in SQ_{3RM} exceeded the measurement error for all groups (Figure 9.3.3).

There was a statistically significant group x time interaction for SQ_{3RM} (Table 9.3.1). This highlighted that ATH increased SQ_{3RM} to a greater magnitude (0.21 BW [95% CI: 0.15, 0.27 BW], $p < 0.01$) compared to the STR (0.08 BW [95% CI: 0.03, 0.12 BW], $p < 0.01$) and TRAD (0.08 BW [95% CI: 0.02, 0.12 BW], $p = 0.01$). Additionally, there was a statistically significant group x time interaction for $TRAD_{1RM}$, despite no main effect for time. This highlighted that STR demonstrated a statistically significant increase in $TRAD_{1RM}$ (2.93 $N \cdot kg^{-1}$ [95% CI: 0.46, 5.40 $N \cdot kg^{-1}$], $p = 0.03$), whereas TRAD demonstrated a non-statistically significant decrease in $TRAD_{1RM}$ (-1.32 $N \cdot kg^{-1}$ [95% CI: -3.80, 1.15 $N \cdot kg^{-1}$], $p = 0.26$). The relative increase in $TRAD_{1RM}$ exceeded the measurement error for STR only (Figure 9.3.3). The POST-intervention $TRAD_{1RM}$ assessment was not completed by ATH.

Vertical Jump Performance. There were no significant main effects of group, time or group x time for CMJ_H and SJ_H (Table 9.3.1). However, the relative increase in CMJ_H exceeded the measurement error for ATH only (Figure 9.3.3). The relative increase in SJ_H exceeded the measurement error for STR only (Figure 9.3.3).

Table 9.3.1. Changes in strength profile, vertical jump performance and VL muscle contractile characteristics following the strength training intervention.

				ANOVA								
		PRE	POST	Group			Time			Group x Time		
Variable	Group	$\bar{x}$ ± SD	$\bar{x}$ ± SD	F	p	η_p^2	F	p	η_p^2	F	p	η_p^2
	TRAD	32.2 ± 4.4	33.7 ± 3.8									
CON_{1RM} ($N \cdot kg^{-1}$)	STR	34.1 ± 4.5	36.3 ± 3.6	1.49	0.26	0.18	22.60	< 0.01	0.62	0.91	0.43	0.12
	ATH	36.8 ± 5.0	37.9 ± 4.6									
	TRAD	33.3 ± 4.9	35.1 ± 3.9									
ISO_{90} ($N \cdot kg^{-1}$)	STR	34.5 ± 4.6	37.6 ± 3.4	0.88	0.44	0.11	22.45	< 0.01	0.62	0.91	0.43	0.12
	ATH	36.8 ± 5.2	38.6 ± 4.7									
	TRAD	35.7 ± 5.5	38.0 ± 5.1									
ECC_{1RM} ($N \cdot kg^{-1}$)	STR	40.4 ± 5.2	44.6 ± 5.4	2.15	0.15	0.24	38.93	< 0.01	0.74	1.56	0.25	0.18
	ATH	42.2 ± 7.1	44.8 ± 7.4									
	TRAD	34.6 ± 5.3	33.4 ± 5.5									
$TRAD_{1RM}$ ($N \cdot kg^{-1}$)	STR	36.5 ± 3.6	39.4 ± 3.5	2.42	0.15	0.20	1.05	0.33	0.10	7.36	0.02	0.42
	ATH											
	TRAD	1.59 ± 0.27	1.66 ± 0.25									
SQ_{3RM} (BW)	STR	1.70 ± 0.19	1.78 ± 0.14	0.54	0.60	0.07	61.23	< 0.01	0.81	7.47	0.01	0.52
	ATH	1.62 ± 0.18	1.83 ± 0.15									
	TRAD	0.38 ± 0.12	0.37 ± 0.10									
CMJ_H (m)	STR	0.36 ± 0.06	0.38 ± 0.05	0.18	0.84	0.03	0.74	0.41	0.06	0.65	0.54	0.10
	ATH	0.34 ± 0.05	0.36 ± 0.04									
	TRAD	0.35 ± 0.14	0.34 ± 0.08									
SJ_H (m)	STR	0.31 ± 0.01	0.34 ± 0.01	0.82	0.46	0.13	0.06	0.82	0.01	0.81	0.47	0.13
	ATH	0.30 ± 0.03	0.29 ± 0.03									

Muscle Morphology and Architecture. Representative images taken at the MID and DIST region of the VL muscle are shown in Figure 9.3.2. There was a significant main effect of group for PA_{MID} (Table 9.3.2). At baseline, ATH were associated with a statistically significantly greater PA_{MID} compared to STR (2.8º [95% CI: 0.0, 5.6º], p = 0.05) and TRAD (4.2º [95% CI: 1.2, 7.1º], p = 0.01). However, after the training intervention ATH did not demonstrate a statistically significantly greater PA_{MID} compared to the STR (1.5º [95% CI: -2.3, 5.2º], p = 0.94) and TRAD (2.8º [95% CI: -1.1, 6.8º], p = 0.21). There were no significant main effects of time for measurements of muscle morphology and architecture. Despite this, the relative change from PRE to POST intervention exceeded the measurement error for CSA_{DIST} and PA_{DIST} for TRAD; CSA_{MID} and PA_{DIST} for STR, and CSA_{DIST}, CSA_{MID}, FL_{DIST} and PA_{MID} for ATH (Figure 9.3.4). There was a group x time interaction for CSA_{DIST}, which highlighted that CSA_{DIST} decreased from baseline for ATH (-3.4 cm^2 [95% CI: -5.1, -1.8 cm^2], $p < 0.01$) but not for STR (0.6 cm^2 [95% CI: -0.95, 2.1 cm^2], p = 0.44) or TRAD (0.8 cm^2 [95% CI: -0.71, 2.31 cm^2], p = 0.28, Table 9.3.2).

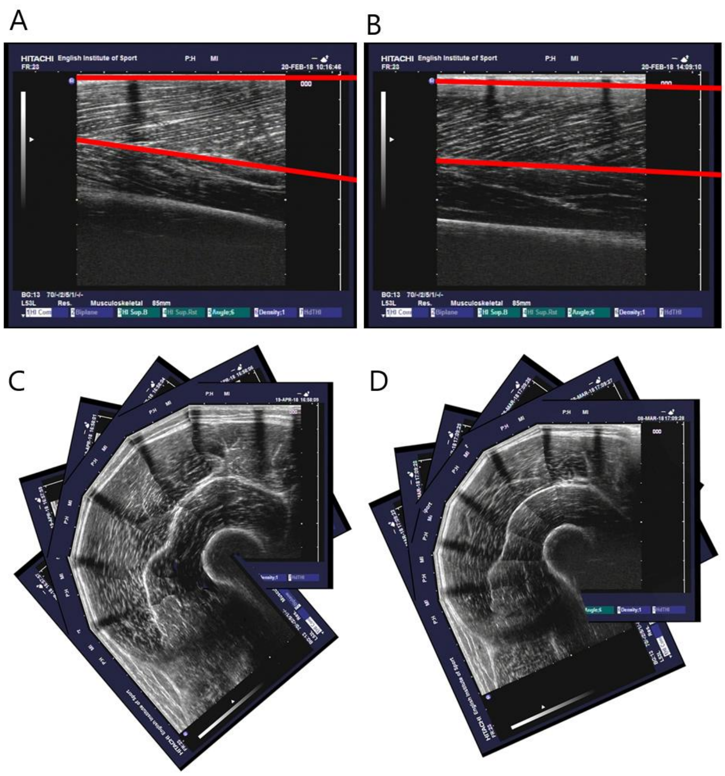

Figure 9.3.2. Representative images of VL muscle architecture at the distal (A) and mid (B) region and VL muscle CSA at the distal (C) and mid (D) region using ultrasonography. Red lines on images A and B are used for linear extrapolation when fascicles extended beyond the field of view.

Table 9.3.2. Changes in measurement of VL muscle morphology and architecture following the strength training intervention.

		PRE			POST			ANOVA								
								Group			Time			Group x Time		
Variable	Group	$\bar{x}$	±	SD	$\bar{x}$	±	SD	F	p	η_p^2	F	p	η_p^2	F	p	η_p^2
CSA_{DIST} (cm^2)	TRAD	18.7	±	4.2	19.5	±	4.6	1.40	0.28	0.17	2.65	0.13	0.16	9.93	< 0.01	0.59
	STR	22.3	±	5.2	22.8	±	5.2									
	ATH	24.8	±	3.4	21.4	±	3.2									
CSA_{MID} (cm^2)	TRAD	29.8	±	8.2	29.9	±	8.2	0.91	0.43	0.13	0.12	0.73	0.01	3.13	0.07	0.33
	STR	33.5	±	3.8	34.4	±	4.2									
	ATH	34.6	±	4.7	33.3	±	4.3									
LLM (kg)	TRAD	20.3	±	3.2	20.3	±	3.4	0.61	0.56	0.08	0.30	0.60	0.02	1.10	0.36	0.14
	STR	22.4	±	2.8	22.8	±	3.3									
	ATH	21.1	±	4.5	20.9	±	5.0									
FL_{DIST} (cm)	TRAD	12.4	±	2.4	12.2	±	2.5	1.28	0.31	0.17	0.72	0.41	0.05	0.67	0.53	0.09
	STR	12.6	±	2.6	13.0	±	2.8									
	ATH	10.3	±	2.0	10.9	±	2.0									
FL_{MID} (cm)	TRAD	11.0	±	1.6	10.9	±	2.2	0.57	0.25	0.19	0.00	0.96	0.00	0.13	0.88	0.02
	STR	10.2	±	1.0	10.2	±	1.1									
	ATH	9.4	±	0.7	9.5	±	1.7									
PA_{DIST} (°)	TRAD	15.1	±	1.9	16.0	±	1.1	2.58	0.11	0.29	1.47	0.25	0.10	0.54	0.59	0.08
	STR	16.6	±	1.8	17.4	±	1.4									
	ATH	18.2	±	2.5	18.1	±	2.7									
PA_{MID} (°)	TRAD	16.2	±	1.9	15.9	±	1.4	4.83	0.03	0.43	0.54	0.14	0.16	0.99	0.40	0.13
	STR	17.5	±	1.9	17.3	±	2.0									
	ATH	20.3	±	1.2	18.7	±	3.1									

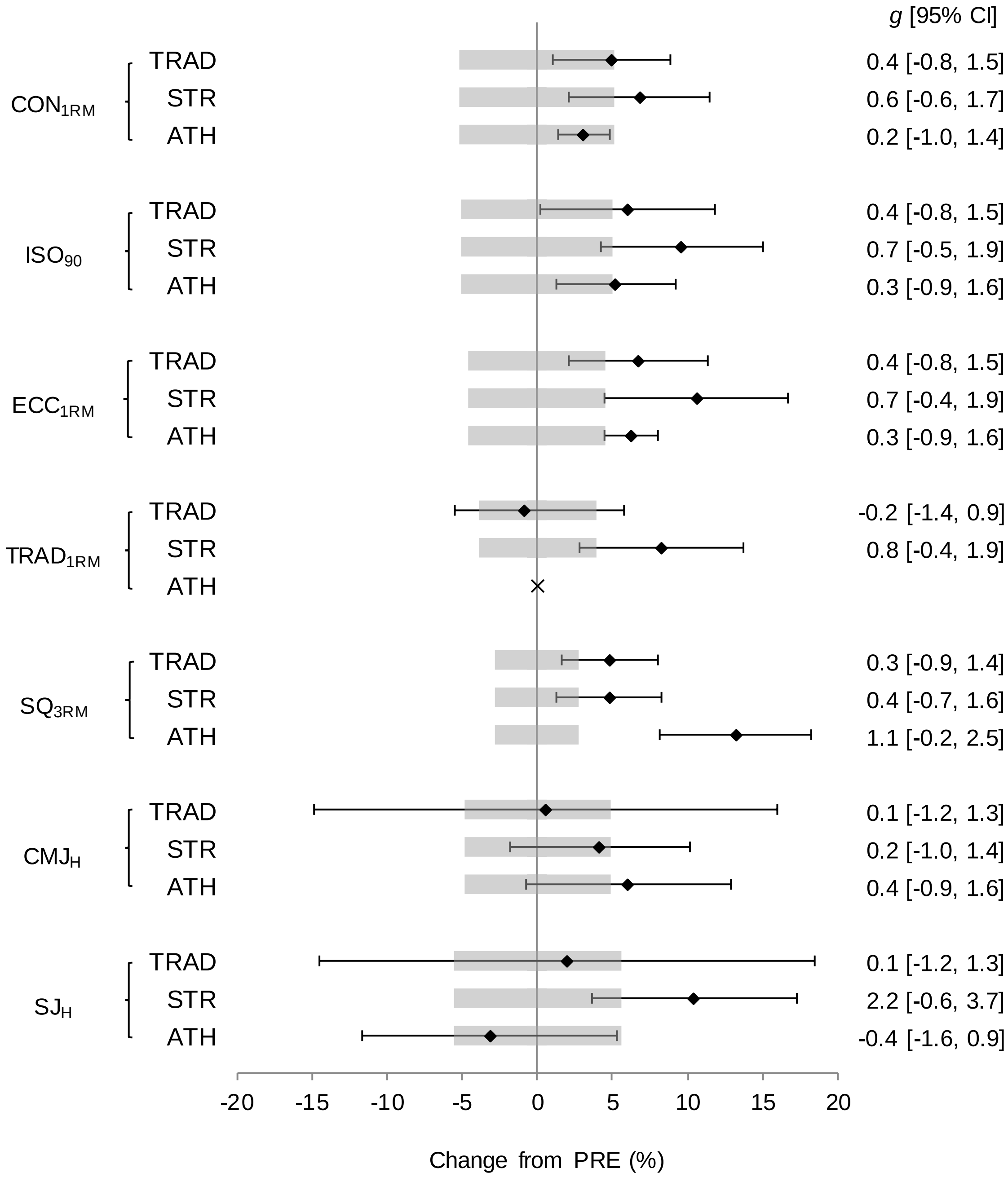

Figure 9.3.3. Relative changes in strength profile and vertical jump performance from PRE to POST-intervention. Filled circles and bars represent mean ± 95% CI, respectively. Light grey bars represent the measurement error. On the right side of graph displays effect sizes [95% CI].

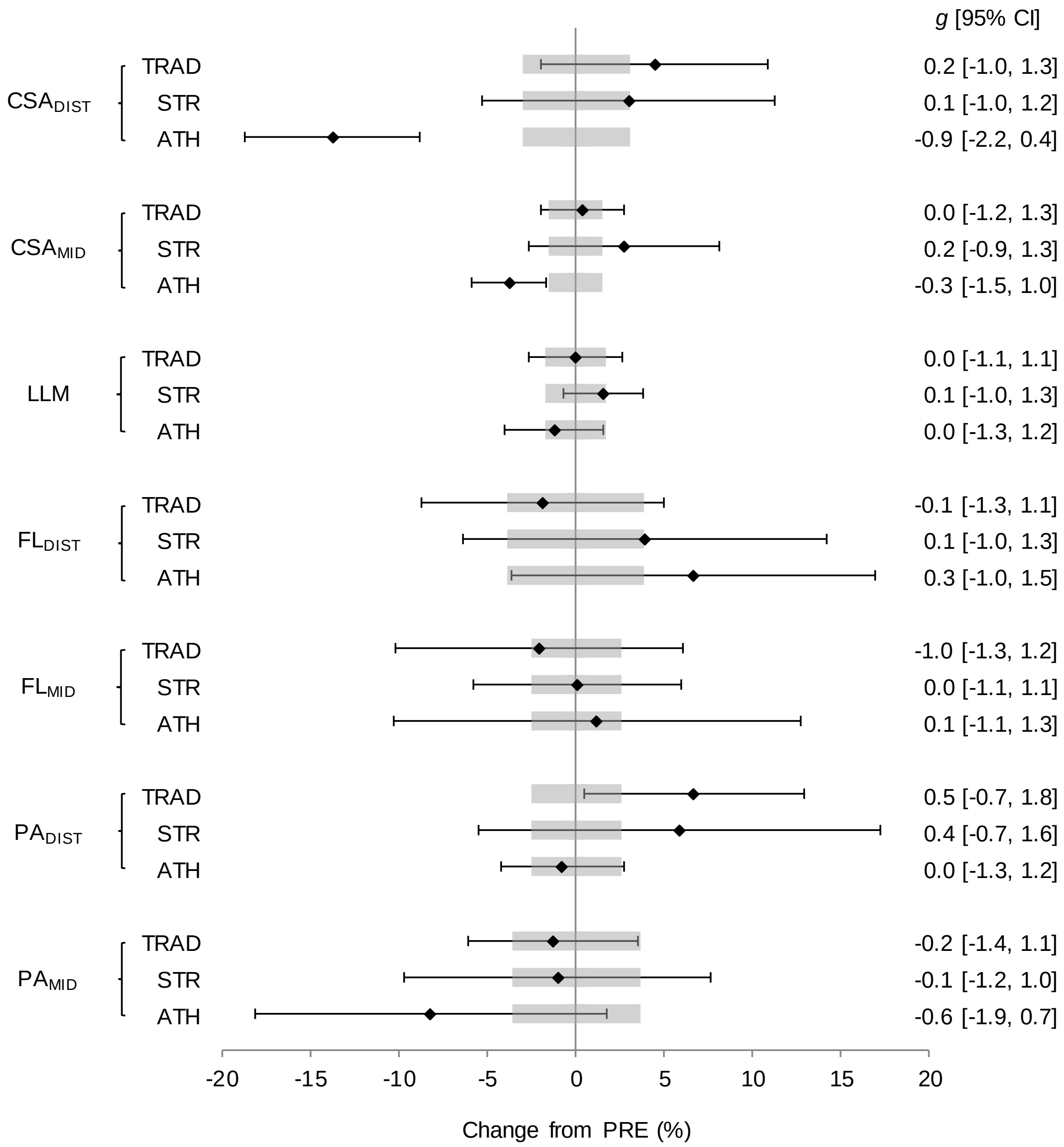

Figure 9.3.4. Relative changes in measurements of VL muscle morphology and architecture from PRE to POST-intervention. Filled circles and bars represent mean ± 95% CI, respectively. Light grey bars represent the measurement error. On the right side of graph displays effect sizes [95% CI].

9.4 Discussion

The aim of this study was to ascertain the feasibility of a strength training programme which incorporates a progressive, task-specific approach to eccentric load prescription by; (a) establishing the effects of this approach on muscle function and ultrastructure in well strength-trained individuals and, (b) observing the response of elite sprint cycling athletes when incorporating this approach to strength training alongside sport-specific training. This information addressed the seventh aim of this thesis. The application of a progressive, task-specific approach to eccentric load prescription was well-tolerated throughout the allocated training period. In general, the strength training programme (with and without the task-specific approach to eccentric load prescription) was successful in increasing strength across numerous components of the strength profile. Based on statistical analyses, the beneficial effects of using a task-specific approach to eccentric load prescription was not well defined. However, when considering a more practically applicable means of interpretation, such as considering thresholds for measurement error and effects sizes, a number of outcomes were revealed.

The data imply that for some individuals the task-specific approach to eccentric load prescription could be a subtly more efficient method of increasing strength across several components of the strength profile, predominantly $TRAD_{1RM}$ and SJ_H. Similarly, the effects on muscle morphology and architecture were subtle which could be, in part, explained by the short training period (4 weeks) and low total number of sessions (8 sessions). Incorporating the strength training programme alongside sport-specific training with a group of elite athletes resulted in a distinct response for strength, muscle architecture and muscle morphology. This could be a result of the additive and unique training demands of track sprint cycling and the characterisitcs of the athlete group. Although the prescribed training was well-tolerated by the ATH group throughout the allocated training period, there was an indication that the ATH group required a different approach to recovery and deload versus the non-athlete groups.

The progressive, task specific approach to eccentric load prescription resulted in the STR and ATH groups exercising with 23-30% greater intensity during the leg press exercise, which was prescribed using progressive loading approach from 85-100% relative 1 RM for the eccentric and concentric phase across the training period. This approach was suited to prompting the greater force producing capacity associated with eccentric muscle actions, whilst accounting for individual differences in magnitude of specificity of force output. This information supports previous observations of the greater force producing capacity expressed during eccentric actions *in vivo* (Aagaard *et al*., 2000; Franchi *et al*., 2014; Hortobágyi and Katch, 1990).

Despite Douglas *et al.* (2018) considering a non task-specific approach to eccentric load prescription, a similar magnitude of AEL was used (18–25% above concentric load) alongside a more modest progressive loading approach (68-81% 1RM) throughout the training period compared to the present study. Similarly, the authors found subtle alterations in muscle morphology and increases in strength. Others have adopted a more rigid approach to prescription throughout the training phase which comprise a higher intensity; prescribed a 6 RM or 10 RM plus an additional 40% for the AEL (Walker *et al*., 2016) and 120% 1 RM for EO exercise (Cook *et al*., 2013). The seemingly greater intensity offered during these investigations, and the greater disparity in eccentric and concentric phase load could underpin some of the more pronounced adaptive responses. Although, the differences in study design and participant characteristics are likely to have played a role in the nature and magnitude of the adaptive responses. Future research should consider investigating the effectiveness of different exercise intensities when using a task-specific approach to eccentric load prescription and the effects they have on the magnitude of increase strength and alteration in the architecture and morphology of muscle tissue.

The adaptations in response to the application of AEL in the present study are in line with reports from a number of studies that have demonstrated the efficacy of eccentric training stimuli for increasing maximum eccentric, isometric and/or concentric strength (Coratella *et al*., 2015, 2018; Franchi *et al*., 2014, 2015; Kaminski *et al*., 1998; Pensini *et al*., 2002; Reeves *et al*., 2009; Spurway *et al*., 2000; Walker *et al*., 2016), coupled eccentric-concentric strength (Cook *et al*., 2013; Douglas *et al*., 2018) and SJ performance (Friedmann-Bette *et al*., 2010a). Despite the CMJ being a coupled eccentric-concentric movement, only the ATH group demonstrated an improvement. Previously, athlete groups have responded positively to AEL in terms of CMJ performance (Cook *et al*., 2013). In the present study it is not clear why the athlete group showed a distinctive improvement in CMJ performance. Nevertheless, the magnitudes of change in strength and performance were comparable to those for strength-trained individuals (Cook *et al*., 2013; Douglas *et al*., 2018; Friedmann-Bette *et al*., 2010a; Walker *et al*., 2016) and less than those demonstrated by resistance trained naïve individuals (Higbie *et al*., 1996; Hortobágyi *et al*., 1996a, 1996b; Roig *et al*., 2009) as expected. Plus, the nature of the response aligned with previous reports and therefore the results of this investigation provide further support toward the use of an eccentric training stimulus to enhance muscle function.

Generally, following AEL or EO training, eccentric strength shows the greatest magnitude of improvement (Roig *et al*., 2009). This could be explained by the general lack of emphasised eccentric tasks in conventional training regimes, which provides greater potential for a change in eccentric strength to occur (Gillies *et al*., 2006). This could be as simple as learning to execute the eccentric skill more efficiently (Hahn, 2018) or the provision of a novel stimulus to the neuromuscular system, or a combination of both factors. Alongside an increase in eccentric strength, on numerous occasions researchers have observed a concomitant increase in isometric strength (Cadore *et al*., 2014; Hortobágyi *et al*., 1996b; Walker *et al*., 2016) which tends to be greater than the magnitude of increase in isometric strength following concentric or traditional training (Cadore *et al*., 2014; Hortobágyi *et al*., 1996a, 2000; LaStayo *et al*., 2000). Yet EO training results in a far lesser magnitude of increase in concentric strength versus eccentric strength (Roig *et al*., 2009). In the present study, the inclusion of coupled eccentric-concentric exercise when applying AEL has resulted in collective increase in strength across the components of the profile. For the athlete, the inclusion of AEL is therefore time efficient; concomitantly increasing strength qualities would suit athletes that have limited time devoted to resistance training because of congested competition schedules.

The subtly larger improvements in concentric, isometric and eccentric strength versus the TRAD group, perhaps, infer the potential for greater magnitude of change had the training period continued for a longer duration. This notion is supported by the findings presented by Walker *et al.* (2016) which highlight that the benefits of AEL for strength-trained individuals may take some time to manifest (more than five weeks). Therefore, a longer period of training comprising of a greater number of sessions than what used in the present study may have been better suited to detect more definitive differences in the effects of AEL versus TRAD training. Although, given the high-intensity nature of the prescribed training there would be a concern that this would prompt non-functional overreaching. Alternatively, there is a possibility that the training effects have a delayed response which would have materialised had the investigation allocated a greater period of recovery or unloading prior to performing the post-testing battery.

Perhaps the most distinct difference in responses prompted by between traditional loading versus the task-specific approach to eccentric load prescription was the effects on leg press $TRAD_{1RM}$ and SJ performance. The importance of the magnitude of eccentric phase load when aiming to improve $TRAD_{1RM}$ has been documented in a study by English *et al.* (2014b). The study showed that under-loading the eccentric phase during traditional exercise limited the improvements in leg press $TRAD_{1RM}$ by approximately 12% versus the application of high-intensity AEL. With regards to the SJ, previously published information has highlighted that the application of high-intensity AEL resulted in a greater increase in type IIX fibre CSA, percentage of type IIA fibres expressing myosin heavy chain IIx mRNA and an increase in the level of mRNAs preferentially expressed in fast, glycolytic fibres, making the musculature better suited for expression of explosive strength, which was brough to life with observations of an increase in SJ performance (Friedmann-Bette *et al*., 2010a). This information implies that the greater mechanical load offered through the application of AEL is likely a main driver underpinning these specific adaptive responses.

The most striking alterations in strength was associated with the SQ_{3RM} for the ATH group. The magnitude of the improvement for SQ_{3RM} outweighs those reported previously when using elite athletes cohorts (Cook *et al*., 2013; Douglas *et al*., 2018). Furthermore, this observation is not in line with the STR group who, despite benefiting from AEL in their $TRAD_{1RM}$ on leg press, did not show the same response during the SQ_{3RM}. Conversely, the improved expression of strength for the ATH group did not translate across the leg press strength profile and only affected ECC_{1RM}. It is not clear why the ATH group responded so potently during SQ_{3RM} assessment. According to the perfromance of the STR group it appears that strength improvements are task-specific. If a similar magnitude of improvement had been presented by the ATH group across the other assessments, then it could have indicated that ATH were more responsive to the prescribed AEL training stimulus. However, the lack of supporting outcomes impedes firm conclusions from being drawn.

A possible explanation for the lack of improvement in leg press strength profile is that the ATH group was experiencing a high level of fatigue following the first post-intervention session which comprised of SQ_{3RM} and CMJ assessment. Coincidently, both of these assessments showed notable improvements compared to baseline. Although this is based on anecdotal evidence which does not hold scientific rigour, it does offer a plausible explanation for the lesser magnitude of improvements in the strength profile performed on leg press (in which the $TRAD_{1RM}$ assessment was abandoned) and SJ, which comprised the second session of the post-intervention strength testing. The requirements for the organisation of post-testing and time allocated for recovery needed to be adapted for the ATH group to account for the different circumstances that surround elite sport participation and the added intensity of concurrently perfoming the training intervention alongside high-intensity sport specific training, especialy during periods of testing whereby efforts are maximal.

Previous research has established that concentric exercise tends to lead to an increase in PA (Franchi *et al*., 2015), eccentric exercise tends to lead to an increase in FL (Baroni *et al*., 2013; Franchi *et al*., 2015), whereas coupled eccentric-concentric exercise can be used to simultaneously develop both architectural qualities (Seynnes *et al*., 2007). The adaptive responses may be region specific (Franchi *et al*., 2014; Narici *et al*., 1989; Seynnes *et al*., 2007; Vikne *et al*., 2006). The results show that the TRAD group presented a small increase in CSA_{DIST} and PA_{DIST}. Similarly, the STR group presented a small increase in CSA_{MID} and PA_{DIST}. Which are expected responses given the inclusion of the concentric exercise within the training programmes. However, the STR group showed an increase in CSA_{DIST}, LLM and FL_{DIST} marginally in excess of the threshold defining a practically meaningful change. Hence, the application of AEL could have initiated alterations in these qualities with a longer period of training comprising of more than eight sessions in total. That said, a number of researchers have documented early adaptive response (four to five weeks) (Baroni *et al*., 2013; Blazevich *et al*., 2007; Franchi *et al*., 2015; Seynnes *et al*., 2007). Given the marginal magnitude of change, the results must be interpreted with a degree of caution. Although the outcomes in the present study may not be as definitive as those in past research, it is promising that the subtle adaptations allude to what has been reported previously.

The most striking alterations in muscle morphological and architectural profiles were associated with the ATH group. This group presented a distinct reduction in VL CSA_{MID} and CSA_{DIST}. Interestingly, this was in contrast to the expected response based on previous research (Roig *et al*., 2009) and the response of the comparable group (STR). Previously, changes in measures of muscle morphology have been attributed to altered muscle architecture (Franchi *et al*., 2017). Accompanying the decrease in CSA were less distinct alterations in PA_{MID} and FL_{DIST}. The reduction in PA_{MID} was in contrast with the response of the STR group. The increase in FL_{DIST}, although similar in nature was slightly augmented compared to the STR group. Previous evidence lends towards coupled eccentric-concentric exercise with the application of AEL resulting in a simultaneous increase FL and PA (Seynnes *et al*., 2007). Most likely because of the inclusion of both the concentric and eccentric phase during training. This is reflected in the response of the STR group. However, there is some evidence to show that when implementing this type of training with rugby athletes, it resulted in a decrease in PA concomitant with an increase in FL (Douglas *et al.,* 2018). The latter evidence better reflects the nature of the response of the ATH group. An explanation to support the distinct response from the ATH group could simply be due to the additional physical demands imposed by additional sport-specific training. However, it is also plausible to suggest that the potential differences of the athlete's architectural and morphological characteristics could play a part.

The ATH group presented greater PA_{MID} at baseline compared the other groups. Furthermore, when considering the other measurements pertaining to morphological and architectural characteristics for the ATH group, they are seemingly disparate to the other groups. With slightly greater PA and shorter FL at baseline, the ATH group presented a practically meaningful relative decrease in PA_{MID} and increase in FL_{DIST} in response to training. A potential stimulus for architectural adaptation could be lower baseline values. In support of this notion, a study by Coratella *et al.* (2018) found that individuals with different baseline architectural characteristics presented an altered responses to eccentric training. Although, this study was primarily examining gender differences, the result indicated that individuals with smaller PA at baseline presented a greater increase in PA following eccentric training than individuals with greater PA at baseline (14% versus 5%). Similarly, those individuals with shorter FL at baseline presented a greater increase in FL in response to eccentric training than individuals with longer FL at baseline (12% versus 7%). An athletes morphology and architectural characteristics can differ and will reflect the nature of their training, training history and physical characteristics (Abe *et al*., 2000; Ema *et al*., 2016b; Funato *et al*., 2000; Kawakami, 2005; Kearns *et al*., 2000). Therefore, what is considered a relatively homogeneous cohort in terms of strength training experience and strength level may, in fact, be heterogeneous based on their muscle architectural and morphological characteristics. In order to attain more definitive outcomes in response to AEL regimes it might be necessary to recruit individuals with similar baseline morphological and architectural characteristics to ensure individual responses do not dilute potentially meaningful information.

Alternatively, the multi-joint nature of the prescribed exercise means that a number of muscle groups are likely to be instrumental in performing the prescribed exercise and therefore the mechanical stress would be distributed across numerous muscle groups. It is possible that the potency of the mechanical strain to the VL muscle might not be enough to create well-defined adaptive response compared to other muscles. Hence, the VL muscle may not accurately depict the architectural and morphological response to the prescribed exercise.

In summary, the application of a progressive, task specific approach to eccentric load prescription was well-tolerated throughout the allocated training period. When considering a more practically applicable means of interpretation the data imply that for some individuals the task-specific approach to eccentric load prescription could be a subtly more efficient method of increasing strength across several components of the strength profile and present subtle difference in alterations of muscle morphology and architecture. This could be, in part, explained by the short training period and low total number of sessions. A number of the response of the elite sprint cycling athletes were distinct, which could be a result of the additive sport-specific training demands or differences in architectural characteristics pre-training. Although the prescribed training was well-tolerated by the ATH group, they would have benefited from individualised organisation of post-testing and time allocated for recovery for the added intensity of concurrently perfoming the training intervention alongside high-intensity sport specific training.

Unfortunately, the variability in individual responses to the prescribed exercise, in conjunction with the small sample size broadened the range of the CI’s. Alongside a relatively short training duration, the outcomes are less definitive in places and impede firm conclusions being drawn. An attempt has been made at interpreting the findings using the measurement error as the threshold for defining practically meaningful change, alongside considering the magnitude of the effect sizes. In conjunction with support from previous insights the discussion endeavoured to bring to light the practical relevance of the findings from the present study. This is an important aspect of the interpretation, given that marginal changes in performance can be valuable to performance in elite level sport.

9.5 Applied Perspective

This investigation contributes towards addressing the seventh aim of this thesis, which was to ascertain the feasibility of a strength training programme which incorporates a progressive, task-specific approach to eccentric load prescription by; (a) establishing the effects of this approach on muscle function and ultrastructure in well strength-trained individuals and, (b) observing the response of elite sprint cycling athletes when incorporating this approach to strength training alongside sport-specific training. The specifically designed eccentric strength assessment (verified in Chapter 8) was used as more accurate platform to prescribe individualised eccentric training loads and as a more definitive evaluation of eccentric strength following the intervention. It enabled logical progression of eccentric training loads in accordance with what is already known about the application of strength training. The strength profile approach (verified in Chapter 8) provided some insight into the adaptive response of different strength qualities in response to training. Importantly, this investigation applied the methods to a small cohort of full-time elite track sprint cycling athletes who performed the S&C programme and sport-specific training, concurrently.

A significant observation, which is grounded on more anecdotal evidence was the timing of the post-intervention assessment relative to the training requirements. Incorporating the AEL stimulus concurrent with other high-intensity strength exercise and in conjunction with sport-specific training for the athlete group may have required better timing of the post-training reassessment. Furthermore, participants across all groups were generally expressing heightened performance during the final week of the training intervention, given that the prescription parameters required participants to achieve maximal or new heightened levels of performance. The 7-day unloading period seemed somewhat redundant and did not appear to contribute towards prompting expression of further improvements in performance. Particularly for the athletes the maximal nature of the final week of training incurred a level of fatigue which impeded aspects of the post-intervention reassessment battery. Whilst the TRAD and STR group may have required an altered stimulus during the unloading, the ATH group were more likely to have needed a greater period of unloading in order to realise the full extent of the adaptations across all areas of strength. This experiential insight should be considered by researchers who are planning to develop eccentric training interventions and S&C practitioners looking to implement high-intensity eccentric exercise with their athletes.

Chapter 10

General Discussion

10.1 Chapter Overview

This section of the thesis will first provide a summary of the investigations comprising this work, then will discuss the significance of the main findings in the applied context and the contributions made towards improving S&C practice. Recommendations for future research have been suggested, which have materialised over the course of investigation and are believed would contribute towards advancing knowledge in the topic area and, importantly, be impactful to S&C practice.

10.2 Summary of the Investigations

The overarching aim of this thesis was to better understand the evaluation, prescription and application of novel high-intensity eccentric exercise in a high-performance context in order to evolve S&C practice. This was achieved via several investigations. The first investigation (Chapter 3) was exploratory in nature and acquired experiential knowledge from high-performance S&C practitioners, which inspired the development of a practically applicable series of investigations for this thesis. The second investigation (Chapter 4) increased our understanding of the functioning of a bespoke leg press device which can operate as a conventional, isometric and an eccentric device. The chapter also briefly provided preliminary insight into the mechanical differences underpinning each exercise mode which provided a loose framework for subsequent studies. The third and fourth investigations (Chapter 5 and 6) provided new insight into the typical performance responses of strength-trained individuals during isometric strength evaluation (Chapter 5) and high-intensity eccentric exercise (Chapter 6). These investigations highlighted the potential for force output during isometric assessment and drew attention to the potency of the mechanical stimulus achieved using eccentric exercise.

The fifth investigation (Chapter 7) raised awareness of the immediate training-induced effects of high-intensity, multi-joint eccentric exercise and the highly varied profiles of individual responses. The outcomes provided information which could assist with the organisation and management of the training stimulus (or a similar stimulus) within a broader physical preparation schedule. Importantly, the highly varied profiles of individual responses drew attention to potential issues with eccentric training load prescription. The potential disproportion in muscle force output expressed during isometric versus eccentric exercise would result in individuals working at different intensities relative to their eccentric strength. Therefore, a task-specific assessment of eccentric strength was developed in the sixth investigation (Chapter 8) to establish a more definitive evaluation of eccentric strength. This was intended to provide a more accurate platform to prescribe individualised eccentric training loads. Consequently, a task-specific approach to eccentric load prescription was applied in the seventh investigation (Chapter 9) which comprised a four-week strength training intervention to determine the effects on strength, muscle morphology and architecture in strength-trained individuals and, uniquely, the response of a group of elite track sprint cycling athletes.

10.3 Main Findings

10.3.1 Mechanical Characteristics of High-Intensity Eccentric Exercise

This work has increased the awareness of the mechanical characteristics of high-intensity eccentric exercise. The findings revealed that heavier relative external load used during the eccentric phase of the leg press exercise stimulated greater average force output which, in turn, was associated with a faster descent velocity and shorter TUT is somewhat obvious. Nonetheless, this information has provided some evidence quantifying the interaction of intensity and TUT which are two key training variables. The information can complement previous investigations that have addressed the interaction between intensity and the maximum repetition capacity, but do not consider TUT, for eccentric efforts (Kelly *et al*., 2015; Moir *et al*., 2013). Unfortunately, in the present work, the number of repetitions was not addressed and therefore was limited in direct comparison with those studies conducted previously. Nonetheless, the information acquired here can be built upon to develop a set of guidelines and example schemes for eccentric exercise, which account for the differences in force producing capacity and fatigue patterns. This would be a similar resource to the training-load chart provided by the National Strength and Conditioning Association for conventional exercise. Ultimately, developing a resource of this nature would assist practitioners as they design eccentric resistance exercise regimes for their athletes. This work has addressed the very early stages of such a resource and future research should consider evolving this approach to assist S&C practitioners with the prescription of high-intensity eccentric exercise in athletes S&C regimes.

Importantly, the information underpinning the results revealed that eccentric force output under each loading condition was less than the force imposed by the external load. The faster the descent velocity, the greater the discrepancy between the force imposed by the external load and the force produced by the individual. Crucially, prescribing a similar external load but performing the descent with a *faster* versus *slower* velocity could result in the intensity of the *faster* exercise being less than that of the *slower* velocity exercise. This has important implications for those investigations that have considered comparing the effects of eccentric exercise with different velocities. For example, the results of a recent study conducted by Douglas *et al.* (2018) demonstrated that there was no adaptive response following *fast* eccentric (1 seconds tempo) versus *slow* eccentric (3 seconds tempo) protocol whereby the relative intensity of the applied load differed by ~12%. According to the findings of the present work, the force imposed by the external load may not have been too dissimilar between conditions. If this was the case, the exercise stimulus under the *fast* condition would have been reduced compared to the *slow* training condition, i.e. similar exercise intensity but less total TUT. This is likely to have affected the subsequent adaptive response. Essentially, in the prescription of eccentric exercise one must consider the degree of unweighting that involved in descending the carriage which can alter the underpinning mechanics and, thus, the intensity of the exercise stimulus.

Moreover, the investigation raised an important point pertaining to the execution of high-intensity eccentric repetitions. The increase in acceleration towards the end ROM could indicate that the load is not well tolerated in more flexed positions and is too great to resist at a given target velocity. This can signify that the load is outside the individual’s eccentric strength limit for the target ROM and target velocity which could be deemed a failed repetition. Performing the exercise with this level of intensity can have implications for safe execution and may incur a degree of muscle damage from forcibly lengthening the muscle at fast velocity. This could have repercussions of muscle soreness in the days following. Alternatively, the individual may be voluntarily reducing force output and losing muscle tension towards the end ROM in anticipation of the end of the repetition whereby the carriage comes to rest on the safety stops. From a coaching perspective, it is important to recognise this and encourage the individual to maintain muscle tension and promote continued force production throughout the whole ROM. This would maximise the performance of eccentric exercise and enable coaches to appropriately evaluate the suitability of the applied load.

Overall, this segment of the work enabled a better understanding of the mechanics underpinning high-intensity eccentric exercise such that the exercise could be coached and performed more effectively, as well as prescribed and implemented more appropriately. This formed the framework for a more meticulous application of high-intensity eccentric exercise, which underpinned performance of the protocol for the studies conducted in the series of investigations comprising this work.

10.3.2 Specificity of Force Output & Strength Profiling

This work supported the notion that eccentric muscle actions have greater force potential than isometric and concentric muscle actions when performed under the same positional constraints. Importantly, it provided an indication of the force potential of strength-trained individuals during eccentric leg press exercise versus conventional exercise. The data rationalised the use of greater load during the descending phase of the exercise in order to offer the same relative exercise intensity compared to an isometric or concentric effort. Furthermore, the investigation held ecological validity as the exercise which was used is commonly used by several high-performance sport groups during training. Additionally, the investigation did not draw upon more constrained isokinetic assessment which is often the mode used to capture the specificity of force output. Unfortunately, this aspect of the work is limited in that it is not clear to what magnitude eccentric force output would differ from isometric or traditional exercise under different eccentric tempo, compared to the five seconds descent which was applied in the present work. This could be an area for future research to attend to. Nonetheless, from a practical perspective the results provided an indication of the magnitude of eccentric force producing potential above what can be expected during more conventional modes of exercise for strength-trained individuals. This can be considered more relevant to S&C professionals working with athletes compared to a great deal of studies that have used untrained populations.

Interestingly, when altering the position of the isometric test to a more mechanically advantageous position, isometric force output was greater than that during the eccentric assessment. Hence, greater muscle tension and exercise intensity may be offered by non-eccentric exercise with partial ROM versus high-intensity eccentric exercise at a greater ROM. This provides an option for applying very high-intensity exercise if performing the eccentric action is not feasible, or necessary. It is not clear to what magnitude eccentric force output would differ from isometric or traditional exercise under different knee joint-angle constraints, aside from 90° which was employed in the current study. This could be an area for future research to attend to. Nonetheless, from a practical perspective this finding highlighted the variability in force producing capacity across a given ROM. This has implications for the performance of eccentric exercise. For isotonic exercise, the magnitude of the load is usually dictated by strength at the end ROM and the applied load is unlikely to match the strength curve of the individual. For the initial portion of the ROM for eccentric exercise the intensity will be submaximal, and the carriage will be actively lowered. The intended intensity of the exercise will be experienced towards the end ROM, whereby the individual must not voluntarily reduce force output and lose muscle tension in anticipation of the end of the repetition (discussed in the previous section). From practical experience, performance at the end ROM must be deliberate which involves resisting downwards acceleration of the external load. This tends to correspond with the feeling of pushing against the foot carriage and attempting to overcome the downwards motion of the carriage, when in fact the motion of the carriage will not be reversed until the additional load is relieved. The role of the S&C professional is to determine the magnitude of the overload such that it is not excessive. It is this aspect which the latter portion of the current work aimed to establish.

Overall, the study of the specificity of force output established that a task-specific assessment of eccentric strength was repeatable, akin to isometric and conventional modes of assessment. Collectively, the components of the test battery can be used to attain a strength profile which can be used to highlight the potential training needs of the athlete and provide an accurate platform for the prescription of training loads.

10.3.3 Immediate Training-Induced Responses to Eccentric Loading

This work has increased awareness of the immediate training-induced effects of high-intensity multi-joint eccentric exercise. The findings revealed that performing a bout of high-intensity eccentric exercise impaired force producing capacity, SJ performance and VL muscle contractile characteristics, and altered muscle architecture, predominantly in the distal region of the VL muscle. Interestingly, CMJ performance was not affected. Characterising the acute response to novel eccentric exercise has facilitated a better understanding of the training adaptations that could be expected from habitual use of high-intensity eccentric exercise. From a practical perspective, quantifying the acute impact and evaluating tolerances to this type of exercise were used to inform other aspects of the training process, i.e. estimating the time needed for recovery, optimising the acute training stimulus and informing the overall management of the training stimulus (or a similar stimulus) within a broader performance programme, for example when planning multi-session training days. These are fundamental practices of an S&C professional.

Unfortunately, the present work did not monitor the time-course of recovery. Therefore, it is unknown whether the magnitude of the initial response was exacerbated, or diminished, in the hours and days following the exercise bout. This would have enabled a direct assessment of the time-course of recovery which would have offered a more definitive platform for the management of the training stimulus, i.e. determining session frequency and organising appropriate training on the days following the eccentric exercise stimulus. At present, only an assumption can be made based on the magnitude of the immediate training response and anecdotal evidence lends towards some of the 'high-responders' needing numerous days to recover. It would seem appropriate to conclude that a lower volume of high-intensity eccentric exercise with a group of athletes who are required to train numerous times per week may be a more appropriate approach. Therefore, future research areas should include evaluation of response to different dosages of high-intensity eccentric exercise to determine their suitability in addresses a range of desired adaptations. More specifically, attend to minimal dose-response effects and micro-dosing of the training stimulus to facilitate the inclusion of high-intensity eccentric exercise into an athletes training schedule.

10.3.4 Individualised Response to Eccentric Loading and the Implications for Eccentric Training Load Prescription

Individual responses to eccentric loading were observed in several instances. In the investigations comprising chapter 7, individuals showed highly varied responses to an initial and repeated bout of exercise. The difference in individual tolerance to the prescribed exercise was not only apparent from the data sets, but also from the perspective of the coach. This provides a degree of support to suggestions that individuals could have different tolerances to eccentric exercise (Pickering and Kiely, 2017). Therefore, the group data did not necessarily offer an accurate reflection of the responses demonstrated by several participants and a more individualised approach to eccentric exercise prescription is needed to ensure an appropriate stimulus is administered to each individual. Researchers working in high-performance sport are urged to consider the individual responses to training interventions in the analyses. This would ensure that the information generated from scientific inquiry can further improve the accuracy of individualised training programmes for athletes.

A limitation of this study is that the discrepancy in muscle force output expressed during isometric versus eccentric exercise is disproportionate between individuals. Therefore, the prescribed exercise which was derived from isometric force output would have exacerbated to the variation in responses to eccentric loading as individuals were likely to have been working at different intensities relative to their eccentric strength. Nonetheless, a number of studies solely focus on the overall effects of a group and have not specifically addressed the individual responses underpinning the data. The aspect of the present work can provide some insight into individual response, which can be used to encourage researchers to consider individual responses to eccentric loading. Especially when the information is intended for use by elite athletes and S&C professionals whereby the prescription of training in high-performance sport is individualised to ensure that the highest levels of performance is achieved.

Following these observations, a task-specific approach to eccentric strength assessment was investigated which is addressed in Chapter 8. In this investigation, individuals clearly presented different tolerances to strength assessment. Usually, estimations of eccentric strength are derived from non-specific measures of strength as a means to prescribe eccentric training loads. However, this aspect of the work provided some evidence that this method is associated with a degree of error. Prescribing eccentric training loads using an estimation method could result in athletes training at an inappropriate intensity. This could result in inadequate strength development or increase the propensity of injury, and in extreme cases might add to the risk of overtraining. This is particularly important in a high-performance environment when eccentric loads are likely to be very high indeed. This finding has important implications for S&C practitioners that currently use the estimation method for prescribing eccentric training loads for their athletes.

To ensure accurate prescription of training loads, the investigation verified direct approach of eccentric strength assessment which compared favourably to other verified methods of assessing muscle force output. Importantly, the assessment was created so it can be easily conducted using the leg press device as well as translate to other leg press devices. Not only has this provided a more accurate platform for eccentric training load prescription but has also presented a means of profiling strength. This can be used to highlight the potential training needs of the athlete and assess the effects of regimes on different aspects of strength. Future research should assess the acute responses to task-specific approach to eccentric loading to assess to variation in individual responses when working at a given relative eccentric intensity. Furthermore, the research should compare these responses to those following traditional exercise. This would highlight whether the organisation of an eccentric exercise stimulus into a broader physical preparation programme needs to be adjusted from the established processes associated with conventional exercise.

Collectively, these investigations enabled a better understanding of the individual tolerances to eccentric loading and provided an insight into the expected variability in responses to eccentric exercise prescribed using non task-specific measures of strength. The task-specific assessment is considered a more accurate alternative to prescribe training a present, which would enable S&C practitioners to prescribe individualised training to a more accurate level than before.

10.3.5 Task-Specific Approach to Eccentric Training Load Prescription

This work has demonstrated that the application of a progressive, task-specific approach to eccentric load prescription satisfied the higher force producing capacity of eccentric muscle actions. The programme was well-tolerated throughout the allocated training period. The novel application seemed logical and incorporated naturally into the programme as a coach would expect other exercises to. Task-specific approaches have been implemented previously with untrained (Franchi *et al*., 2014) and strength-trained individuals (Vikne *et al*., 2006), but neither training approaches are relevant in the current context and do no address the most appropriate approaches to training specifically for lower body strength development. Therefore, the present study provides information to supplement the information derived from other studies to provide additional evidence as to the efficacy of a task-specific approach to eccentric training load prescription.

The beneficial effects of using a task specific approach to eccentric load prescription was not well-defined. However, a number of outcomes imply that for some individuals this approach to eccentric load prescription could be a subtly more efficient method of increasing strength across several components of the strength profile, predominantly $TRAD_{1RM}$ and SJ performance. The sprint cycling athletes showed a lesser improvement across the leg-press strength profile compared to the strength-trained counterparts, yet more definitive improvements in back-squat strength and CMJ performance. Although the prescribed training was well-tolerated by the ATH group throughout the allocated training period, there was an indication of a high level of fatigue at the end of the training period. Personal communication with the athletes revealed that the athletes found concurrent training difficult by the end of the training block. The athletes verbalised that they felt that they would need more time to recover to fully complete the post intervention assessment. Taking this into account, although some data was gathered the interpretation must be taken with caution as it is may not portray the true potential of the prescribed training. It is not certain exactly when fatigue dissipated, but personal communications with the coaches suggesting that performance improvements were manifesting after several weeks, both in the gym and on the bike. It is appreciated that this information is anecdotal, but it suggests that the present study is limited in that it did not consider the delayed training effects. Performing follow-up post-tests in the weeks following the intervention would have been able to offer some insight into this phenomenon and could have led to observations of more distinct changes in strength across the strength profile. Future research should consider examining the delayed training affects associated with different eccentric training regimes which have been prescribed using a similar approach to the present study. This information would inform S&C practitioners of optimal durations for taper periods and effective organisation of different eccentric training stimulus into the training cycle.

Similarly, the effects on muscle morphology and architecture were not well-defined, which again could be explained by the short training period and low total number of sessions. It is possible that a more definitive conclusion could have been drawn had the training period continued for a longer duration to include a greater number of sessions. Alternatively, a higher volume of eccentric exercise per session (similar to that prescribing in the investigation comprising Chapter 7) may be needed to prompt a more distinct architectural and morphological adaptive response. However, because of the high-intensity nature of the exercise non-functional over-reaching and overtraining would then be a primary concern. That said, the morphological and architectural measurement location in the present study present a limitation. Blazevich *et al.* (2006) established that the architecture of one quadriceps muscle could not be used as an indicator of whole quadriceps response because of the variation in architecture among synergistic muscles. Other studies support this notion (Franke *et al*., 2014; Narici *et al*., 1996). Furthermore, the multi-joint nature of the prescribed exercise could have resulted in another major muscle group, such as the gluteal group, presenting a greater response. Therefore, researchers should consider measuring other quadriceps within the group as well as other major muscle groups to gain a greater insight into the adaptive response of muscle tissue to eccentric exercise. Notwithstanding, capturing the adaptive response of one of the largest in influential quadriceps muscles is likely to provide some valuable insight into the potential for eccentric exercise to affect muscle tissue qualities.

Importantly, the elite athlete group demonstrated a more definitive alteration in a selection of muscle architectural and morphological characteristics, namely CSA and PA in the mid region and CSA and FL in the distal region. The morphological response tended to conflict the direction of the response from the strength-trained counterparts. However, this could be underpinned to some extent by differences in architectural characteristics pre-training. This was discussed in more detail in Chapter 9. However, for the purpose of highlighting areas for future research, matching participants for baseline muscle architecture prior to exposure to eccentric training may provide greater insight into the potential for eccentric exercise to affect muscle tissue qualities.

Although, it is not clear whether the different responses of the elite and non-elite athletes were a manifestation of the athletes' concurrent sport specific demands or whether the athlete group adapt different to eccentric loading. If indeed the athletes have a unique response to eccentric exercise stimulus, then it is imperative that future investigations recruit athlete populations when endeavouring to develop eccentric training regimes specifically to impact athletic performance.

Overall, the investigation into the application of a task-specific approach to eccentric training load prescription offers a glimpse into the potential adaptation in strength-trained individuals and elite sprint cycling athletes when incorporated into a strength training programme. This application shows some potential and the investigation can be used as a foundation to develop a broader range of eccentric training strategies in the endeavour to optimise the use of eccentric exercise for improving athletic performance.

10.4 Summary of the Applied Value of the Work

There were three main aspects to this work; (1) evaluation, (2) prescription and (3) application of high-intensity eccentric exercise for highly strength-trained individuals and athletes. These aspects were deliberately investigated with the context of high-performance S&C coaches in mind. This was to ensure that this work can be used to evolve eccentric training practice in a high-performance S&C context. Overall, the aspects of this work intended to develop appropriate and practically meaningful research for use by high-performance S&C practitioners at the English Institute of Sport for use with GB Cycling athletes. The work confirmed the practicality and feasibility of a purpose-built bespoke leg press device for applying a high-intensity eccentric stimulus safely and efficiently. As mentioned earlier in this thesis, this can be a major issue with other applications of eccentric exercise which tend to be time consuming and require several spotters to manually add and remove load. When using the device in its different functions, assessments and exercise requires minimal technical proficiency, avoids compression of the spinal column and is supportive of the trunk. As the assessments and exercise performed on the machine requires multi-joint co-ordination of the lower limb, they can be considered more relevant to sports performance. Importantly, the assessments are reliable and can be easily conducted by users.

The work enabled a better understanding of the mechanics underpinning high-intensity eccentric exercise such that the exercise can be coached and performed effectively, as well as prescribed and implemented more appropriately. The work provided some insight into the task-specific nature of force production. Not only has this provided a more accurate platform for eccentric training load prescription but has also presented a means of profiling strength. This can be used to highlight the potential training needs of the athlete and assess the effects of regimes on different aspects of strength. These assessments can be used by practitioners at the English Institute of Sport and British Cycling to prescribe training to the athletes to a more individualised and accurate level than before.

The exploration of the acute training induced effects on strength and alteration of muscle morphological and architectural characteristics enabled a better understanding of how eccentric exercise performed on the bespoke device can affect different aspects of muscle function and impact muscle tissue. This has provided some direction for the organisation of an eccentric training stimulus into a broader physical preparation programme, estimating recovery needs and highlighted the importance of evaluating individual needs based on the different tolerances to eccentric loading. The latter has prompted practitioners at the English Institute of Sport and British Cycling to take a more comprehensive approach to neuromuscular evaluation to ensure adaptive responses can be captured for each individual athlete and a bespoke test battery is developed based on the individual athlete needs.

Importantly, this work gained an insight into the response of elite sprint cycling athletes which accounts for concurrent sport demands. This is directly applicable to the context in which it is intended to be used. The results reflect the response of athletes versus non-athlete populations, the latter is what the the majority of formal scientific research is comprised. Unfortunately, it was not feasible to attain a direct measure of on-bike performance during the training period. However, in future, the impact of eccentric training on muscle strength or muscle architectural qualities should be related to measures of performance on the track or cycle ergometer in order to make more direct links on how eccentric exercise can be used to influence sport-specific performance. Overall, the information resulting from this investigation specifically contributes to the body of knowledge pertaining to eccentric training practice in the high-performance context. The thesis provides information that assists in bridging the gap between science and practice serving to evolve S&C practice.

10.5 Conclusion

The components of this project have been deliberately designed with practicality in mind. Prior to conducting formal investigation, an effort was made to establish what the target population wanted to know. This was to ensure that the information generated from this work was valuable. Although this project utilised equipment that may not be attainable in other establishments, the content was derived from a practitioner's perspective to ensure that the majority of processes and outcomes can be transferred to an applied context and to strength-trained individuals. Across the range of investigations an attempt was made to appropriately balance practical applicability and scientific rigour. There are several over-arching limitations of the research and criticisms of the work which have been identified and discussed throughout. It is vital that future research considers the suggestions in order to continue to develop eccentric training knowledge for maximising athletic potential. Notwithstanding, the series of investigations in this thesis contributes towards the body of knowledge pertaining to the prescription, evaluation and application of novel high-intensity eccentric exercise for strength-trained individuals and elite track sprint cycling athletes. At the same time, the information can assist S&C coaches with implementing eccentric exercise with other athletes. Collectively, this should contribute towards evolving S&C practice pertaining to high-intensity eccentric exercise.

Chapter 11

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Chapter 12

Appendices

12.1 Appendix 1: Eccentric Training Methods Descriptions

Fast Augmented Eccentric: Elastic energy from fast eccentric action is stored and immediately re-used during the concentric phase. The aim to immediately enhance concentric force-velocity characteristics, e.g. drop jumps.

Resisted Eccentric/Yielding: Exerting muscle force to resist deformation or buckling under eccentric tension, e.g. when 'sticking' the landing of a drop jump or when performing Nordic hamstring exercise.

Accentuated Eccentric: Lift the load concentrically, lower the load eccentrically under control. No emphasis on concentric performance. Concentric load is less than 1RM load, eccentric load is greater than 1RM load.

Accentuated 2/1 technique: Lift the load concentrically using 2 limbs, lower the load eccentrically using 1 limb. Load is less than 1 RM load for the 2-limb exercise.

Tempo/Submaximal Superslow Eccentric: Eccentric lowering is slow and controlled over a set period of time. The load is less than 1RM load and does not change between the eccentric and concentric phase of the exercise.

Slow Augmented Eccentric: Eccentric force is developed under slow/controlled conditions and at the moment of transition to the concentric phase, the external load is reduced/removed to facilitate concentric force-velocity interaction. Eccentric load is greater than concentric load (e.g. using weight releasers or spotters to manually remove weight plates).

Supramaximal Eccentric-only: Lower the load eccentrically only, the concentric phase is completed with assistance via spotters or equipment. Eccentric load is greater than 1RM load.

Combined Method/two-movements: Lift the load concentrically using a compound movement (e.g. deadlift), lower the load eccentrically using an isolation exercise (e.g. RDL). Load is less than 1RM load for the compound lift.

Flywheel Method: Accelerate the flywheel throughout the concentric phase and rapidly decelerate the flywheel during the eccentric phase. Concentric load is determined by the resistance of the flywheel. The eccentric load can be increased by increasing acceleration throughout the concentric phase.

12.2 Appendix 2: Exploratory Research Questionnaire

Information & Consent

We would like you to complete this questionnaire so we can gather your opinions on eccentric training and capture the details of how you use it in your coaching practice. This questionnaire is NOT a test of your knowledge - we want you to share your insights and honest reflections about this unique mode of training. We anticipate that this research will highlight real-world performance problems and draw out key information to help us to devise appropriate and meaningful scientific research, which will work towards advancing applied strength and conditioning practice, specifically in relation to eccentric training.

The questionnaire should take no longer than 15 minutes to complete. All responses you submit will be anonymous. The general findings may be published in a scientific journal and/or presented at conferences. This study has received full ethical approval from Faculty of Health and Life Sciences Research Ethics Committee at Northumbria University

- ☐ I have read and fully understand the information above
- ☐ I understand that I am free to withdraw from this research at any time
- ☐ I agree to participate

Please complete the following:

1. Age (years):

2. Gender:
    - o Male
    - o Female

3. How many years have you worked as a Strength & Conditioning practitioner?

4. Do you hold a Strength & Conditioning related qualification?

    - o Yes, please provide details:
    - o No

5. What is your current job title?

6. Is this role working as part of a:

    - Professional sports club
    - Sports institute
    - Higher education
    - Other, please specify:

7. How many years have you worked in your current job role?

8. Please provide details of the main sports you have worked with. Please start with your most recent sport and enter information for up to 6 sports:
    - Sport:
    - Discipline:
    - Performance Level:
        - Olympic
        - International
        - National
        - Regional
        - Club
        - University/Academic
        - Recreational

9. What quality/qualities have you sought to enhance when using eccentric training?

    Muscle-tendon unit stiffness - Please choose 1 option per row

    - Yes
    - No, but I would consider
    - No, and I wouldn't consider

    Deceleration, landing or change of direction tasks - Please choose 1 option per row.

    - Yes
    - No, but I would consider
    - No, and I wouldn't consider

    Maximum eccentric strength - Please choose 1 option per row.

    - Yes
    - No, but I would consider
    - No, and I wouldn't consider

Maximum concentric strength - Please choose 1 option per row.

- Yes
- No, but I would consider
- No, and I wouldn't consider

Rate of force development - Please choose 1 option per row.

- Yes
- No, but I would consider
- No, and I wouldn't consider

Stretch-shortening cycle performance - Please choose 1 option per row

- Yes
- No, but I would consider
- No, and I wouldn't consider

Concentric power - Please choose 1 option per row.

- Yes
- No, but I would consider
- No, and I wouldn't consider

Eccentric power - Please choose 1 option per row.

- Yes
- No, but I would consider
- No, and I wouldn't consider

Injury prevention & rehabilitation - Please choose 1 option per row.

- Yes
- No, but I would consider
- No, and I wouldn't consider

Muscle mass - Please choose 1 option per row.

- Yes
- No, but I would consider
- No, and I wouldn't consider

Force production at large range of motion - Please choose 1 option per row.

- Yes
- No, but I would consider
- No, and I wouldn't consider

Movement economy - Please choose 1 option per row.

- Yes
- No, but I would consider
- No, and I wouldn't consider

Work capacity - Please choose 1 option per row.

- Yes
- No, but I would consider
- No, and I wouldn't consider

Do you know of any other qualities that are missing from the list above? If so, please specify:

10. Please choose an answer option that best represents your use of the following eccentric training methods. Please see Appendix 1 for each of the training methods*.

Accentuated 2/1 Method*

- Never used, and I'm not inclined to use
- Never used, but I'm willing to use
- I rarely use
- I occasionally use
- I regularly use

Accentuated Eccentric Method*

- Never used, and I'm not inclined to use
- Never used, but I'm willing to use
- I rarely use
- I occasionally use
- I regularly use

Fast Augmented Eccentric Method*

- Never used, and I'm not inclined to use
- Never used, but I'm willing to use

- I rarely use
- I occasionally use
- I regularly use

Slow Augmented Eccentric Method*

- Never used, and I'm not inclined to use
- Never used, but I'm willing to use
- I rarely use
- I occasionally use
- I regularly use

Combined Method*

- Never used, and I'm not inclined to use
- Never used, but I'm willing to use
- I rarely use
- I occasionally use
- I regularly use

Supramaximal Eccentric-only/Negative Method*

- Never used, and I'm not inclined to use
- Never used, but I'm willing to use
- I rarely use
- I occasionally use
- I regularly use

Resisted Eccentric Method*

- Never used, and I'm not inclined to use
- Never used, but I'm willing to use
- I rarely use
- I occasionally use
- I regularly use

Flywheel Method*

- Never used, and I'm not inclined to use
- Never used, but I'm willing to use
- I rarely use
- I occasionally use
- I regularly use

Submaximal Superslow Eccentric Method*

- Never used, and I'm not inclined to use
- Never used, but I'm willing to use
- I rarely use
- I occasionally use

- I regularly use

Do you use or know of any other method that is not listed above?

- No
- Yes, please specify and indicate your frequency of use:
    - Never used, and I'm not inclined to used
    - Never used, but I'm willing to use
    - I rarely use
    - I occasionally use
    - I regularly use

For any of the questions above, if you have chosen an option starting with 'Never used...', please select the reason(s) for your choice? Tick all options that are applicable.

- High injury risk
- Excessive muscle soreness
- Concerns of overtraining
- Equipment access
- Not fully knowledgeable of training method
- Inappropriate athlete population
- Disapproval from coaches/medical staff
- Lack of scientific evidence supporting use
- Supervision issues due to large athlete training group
- Unconvinced about the value of this method
- Other, please specify:

11. Have you prescribed eccentric overload to any of your athletes?
    - Yes, please list the group(s) of athletes you've prescribed eccentric overload training?
    - No

12. What type of equipment do you use/have you used to facilitate eccentric overload? Please tick all that apply.
    - Flywheel (e.g. Exxentrix, kBox, nHANCE, YoYo)
    - Weight releasers
    - Standard squat/power rack
    - Standard plate-loaded machine
    - Isokinetic dynamometer
    - Standard cable-pulley machine
    - Specific or custom-built eccentric exercise machine
    - Other, please specify:

13. Provide up to 3 examples of eccentric overload programmes you've used. Please complete at least one row as fully as possible. If exact values cannot be entered use averages/estimates.

Exercise used	No. of sets	No. of reps	Concentric load	Eccentric load	Eccentric rep tempo	Rest period	Sessions freq.	Programme duration
Squat	1	1-2 reps	Bodyweight	100-110% 1RM	<1s	Unrestricted	1 per week	1 week
Leg Press	2	2-4 reps	Unloaded	111-120% 1RM	1-2s	0-1 min	2 per week	2 weeks
Deadlift	3	4-6 reps	<50% 1RM	121-130% 1RM	3-4s	1-2 mins	3 per week	3 weeks
RDL	4	6-8 reps	50-60% 1RM	131-140% 1RM	5-6s	2-3 mins	4+ per week	4 weeks
Leg Extension	5	8-10 reps	60-70% 1RM	141-150% 1RM	7-8s	3-5 mins		5 weeks
Hamstring Curl	6	10+ reps	70-80% 1RM	151+ % 1RM	9+s	5+ mins		6+ weeks
Calf Raise	7		80-90% 1RM					
Pull-up	8+		90-100% 1RM					
Chest Press								
Shoulder Press								
Bicep Curl								
Tricep Extension								
Plyometric								
Other								

14. What changes did you observe in response to your programme(s) entered in the table above? Please include how you measured/quantified changes.

15. Please include any noteworthy remarks related to the eccentric overload intervention(s)? These can be your own and/or your athletes. For example, how they felt during the exercise, throughout the intervention or any perceived after-effects.

16. What source(s) of information inspire your programme content for eccentric overload training? (Please tick all that apply)
    - S&C colleagues
    - Personal experience
    - Influential S&C coaches/practitioners
    - Professionals/academics
    - Sport coaches
    - Scientific journals
    - Certification/Courses
    - Books
    - Internet
    - Other, please specify:

17. Please detail any limitations or concerns that you associate with eccentric training. These might include barriers you've experienced or hesitations you have about using this training modality.

18. Rate the following out of 10 based on your own views and opinions for both submaximal eccentric and eccentric overload training (0/10 = Not at all, 5/10 = Average, 10/10 = Extremely)

	Submaximal eccentric (<1RM load)	Eccentric Overload (1RM load or greater)
The effectiveness as a tool to enhance sports-specific performance	**1-10**	**1-10**
The effectiveness as a tool to enhance mechanical muscle function (e.g. the ability to produce force, both in magnitude and velocity)	**1-10**	**1-10**
The effectiveness as a tool to enhance muscle size & structure	**1-10**	**1-10**
The effectiveness as a tool for injury prevention/rehab	**1-10**	**1-10**
The importance to include in the gym programmes of athletes whose sport requires minimal eccentric-specific action/skill	**1-10**	**1-10**
Your confidence to use with a group of athletes	**1-10**	**1-10**
Your knowledge about the underpinning science	**1-10**	**1-10**
Your knowledge of the range of training methods that can be used in S&C practice	**1-10**	**1-10**

19. In your opinion, what could help improve your ratings of any of the above?

20. What aspects of eccentric training would you like to see investigated in order to move applied S&C practice forward?

21. Do you have any other comments or thoughts about eccentric training?

12.3 Appendix 3: Participant Informed Consent Form

Faculty of Health & Life Sciences

INFORMED CONSENT FORM

Project Title:

Principal Investigator: Mellissa Harden

please tick or initial where applicable

I have carefully read and understood the Participant Information Sheet.	☐
I have had an opportunity to ask questions and discuss this study and I have received satisfactory answers.	☐
I understand I am free to withdraw from the study at any time, without having to give a reason for withdrawing, and without prejudice.	☐
I agree to take part in this study.	☐

Signature of participant.. Date..............................

NAME IN BLOCK LETTERS...

Signature of researcher.. Date..............................

NAME IN BLOCK LETTERS...

12.4 Appendix 4: Participant Health Questionnaire

Faculty of Health & Life

Sciences

Pre-test Health Questionnaire

Personal Details:

Name: ______________________________Date of Birth: ______ Sex: M / F

Contact Details:

Telephone:_____________________ Email:____________________________________

Emergency Contact Details:

Name: ___________________________ Relationship: ____________________________

Phone: _____________________Email: ____

1. Do you wheeze or feel tightness in your chest during or following exercise or any other time **AND/OR** have you ever been diagnosed with asthma?
   Yes ☐ No ☐

2. Do you ever experience chest pain, heart palpitations, unexplained shortness of breath, or feelings of faintness, **AND/OR** have you ever been diagnosed with a heart condition?
   Yes ☐ No ☐

3. Have any immediate family members been diagnosed with heart disease before the age of 50?
   Yes ☐ No ☐

4. Do you currently have **AND/OR** have had any form of muscle or joint injury that may be made worse by performing exercise?
   Yes ☐ No ☐

5. Have you suspended your normal training, for any reason, in previous months or weeks?
   Yes ☐ No ☐

6. Is there anything to your knowledge or do you have any other medical conditions that may pose a risk to your health and wellbeing when completing the exercise required for this investigation?

Yes ☐ No ☐

7. Are you currently taking any medication or nutritional supplements? (e.g. creatine, whey and casein protein, HMB, etc.)?
   Yes ☐ No ☐

8. Is there anything to your knowledge that may prevent you from successfully completing the exercise and tests that have been explained to you?
   Yes ☐ No ☐

9. Are you pregnant?
   Yes ☐ No ☐

10. If you have answered yes to any of the above, please provide details:____
    ____
    ____
    ____

Declaration:

I agree that I have read and understood all details on this form. All details provided are accurate. I declare that I am physically fit to safely participate in the type and intensity of exercise that is specified on the information sheet

Signature: ___________________________ Date: ____/____/____