The Biomechanical Underpinnings and Subsequent Physiological Adaptations of Accentuated-Eccentric Loading in Strength-Trained Males

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Acknowledgements

The fable of the dragons' gate states that if a carp can swim up the waterfall it would turn in to a dragon. The symbology of persevering through hardship, and overcoming something that seems impossible, is all too relevant to the PhD programme. At times, this PhD seemed like it would be impossible for me to complete, a year of technical issues, followed by a global pandemic meant that the first two and half years were almost lost. But like the carp in the dragons' gate fable, I persevered, and this PhD programme is now coming to its end.

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Abstract

Resistance training is a well-documented practice that has been shown to increase the physical performance of athletic populations. Vast bodies of research, which have resulted in hundreds of publications, have explored the concentric phase of resistance training, for which programming recommendations for applied practice have been generated. However, there are far fewer studies which have examined the effects of the eccentric phase of resistance training, particularly in multi-jointed movement patterns such as the squat. To date, few recommendations exist on how to programme eccentric resistance training, which is further hindered by the dearth of research which have examined the underpinning biomechanical properties of the eccentric phase of squatting. To this end, the primary aim of this thesis was to examine the movement dynamics of the eccentric phase of the squat, and to establish whether modifying the loading parameters during the eccentric phase of the squat elicited superior adaptations compared to traditional loading paradigms.

In a collection of initial exploratory studies presented in this thesis, a novel 'smart-resistance training' device (Kineo Training System) that facilitates loading modification of the eccentric phase of the squat was evaluated. Several exploratory studies were undertaken to assess different components of the Kineo including; the assessment of movement dynamics compared to barbell squatting, the assessment of load and velocity compared to barbell squatting, and the assessment of the reliability and validity of the Kineo isovelocity mode. Data revealed no significant differences for squatting kinematics between squats performed on the Kineo or with a barbell. However, greater loads were capable of being lifted with the barbell (~9%). Assessment of the isovelocity mode identified a small but consistent bias in the prescribed velocity (~0.01 $m \cdot s^{-1}$), but high reliability (coefficient of variation 1.6 to 4%; intraclass coefficient 0.99), with a mean variance of 0.01 $m \cdot s^{-1}$ between repetition to repetition. Therefore, it was concluded that the Kineo can accurately and reliably facilitate squatting in a

similar manner to that of a barbell, but with the added benefit of safely modifying the load in the eccentric phase, thus making the Kineo ideal to assess the primary aims of this thesis.

In the first primary study of this thesis, the force-velocity relationship as expressed during squatting was assessed. 15 strength-trained males performed maximal effort isovelocity squats at three concentric, and three eccentric velocities, whilst ground reaction forces were measured. The force-velocity relationship conformed in shape to pre-existing single-joint relationships. However, the magnitude of eccentric force in relation to estimated isometric force (1.1 times) was lower than what is typically seen in single-joints. There was also a large variance between individuals in this magnitude, which was not influenced by the participants concentric performance. This novel data is the first to explore the force-velocity relationship in the squat for both the concentric and eccentric phase.

In the second primary study of this thesis, movement dynamics and muscle activity of the lower limbs were assessed during squatting. Nine strength-trained males performed squats with concentric loads of 20 to 100% of 1RM, and with eccentric loads of 20 to 150% 1RM. When equal load was used in the concentric and eccentric phase, concentric joint moments were always greater than eccentric joint moments, with the 80% concentric trial (2.19 $N \cdot m \cdot kg^{-1}$) producing a significantly greater knee joint moment than the 80% eccentric trial (1.85 $N \cdot m \cdot kg^{-1}$). Only with the use of accentuated-eccentric loading could this difference be negated, with no further significant increases in eccentric knee joint moment past an eccentric load of 120% (2.16 $N \cdot m \cdot kg^{-1}$). This increase in joint moment was not accompanied by any increase in vastus lateralis muscle activity. There was no effect of accentuated-eccentric loading on hip or ankle joint moments.

In the final study of this thesis, a 6-week resistance training intervention was conducted which compared traditional resistance training loading paradigms to accentuated-eccentric loading,

with the protocol based off the data collected in the previous study. 22 strength-trained males partook in the intervention. Findings indicated that all participants improved their isometric and concentric knee extensor strength (~6-12%) but only those who performed accentuated-eccentric loading displayed improvement in eccentric knee extensor strength (~8-16%). This improvement was accompanied by an increase in eccentric vastus lateralis muscle activity. The accentuated-eccentric loading groups also saw a significantly greater improvement in squat 1RM (~15kg) comparted to the traditional group (~9kg). Small, but statistically significant increases in vastus lateralis muscle thickness was observed across all three groups, with no differences between groups. Although DOMS and RPE were greater initially following accentuated-eccentric loading, these were attenuated to the level of traditional resistance training following eight training sessions. These novel data indicate that accentuated-eccentric loading can be utilised to elicit eccentric-specific strength adaptations, whilst enabling superior/equivalent improvements in strength compared to traditional methods.

This thesis has provided novel data that has expanded resistance training research, with a particular focus on the eccentric phase of the squat. Two studies have been conducted which will help practitioners and researchers better understand the underpinning biomechanical factors that influence eccentric resistance training. Whilst the final study has provided a scientifically justified approach to accentuated-eccentric squatting that has been shown to elicit adaptations which will be of benefit to certain athletic populations.

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree of qualification of this or any other university of other institute of learning. This PhD programme was match funded by Liverpool John Moores University and GLOBUS, who are the manufacturers of the Kineo Training System. GLOBUS had no input on any of the research designs, or interpretation of the data presented in this thesis.

Research Outputs

Armstrong R, Baltzopoulos V, Langan-Evans C, Clark D, Jarvis J, Stewart C, O'Brien TD. 2022. Determining concentric and eccentric force-velocity profiles during squatting. *European Journal of Applied Physiology. 122(3), 769-779.*

Armstrong R, Baltzopoulos V, Langan-Evans C, Clark D, Jarvis J, Stewart C, O'Brien TD. 2022 An investigation of movement dynamics and muscle activity during traditional and accentuated-eccentric squatting. *PLoS One. 17(11), 1-19.*

Armstrong R, Baltzopoulos V, Langan-Evans C, Clark D, Jarvis J, Stewart C, O'Brien TD. 2022. The effects of concentric and eccentric loading on the lower limb biomechanics during squatting. *The British Association of Sports and Exercise Sciences B.I.G 2020 [Online], 25 May 2022: p. 19*

Armstrong R, Baltzopoulos V, Langan-Evans C, Clark D, Jarvis J, Stewart C, O'Brien TD. 2022. A comparison of kinematic and muscle activity of three squat variations. *The British Association of Sports and Exercise Sciences B.I.G 2020 [Online], 25 May 2022: p. 23*

Armstrong R, Baltzopoulos V, Langan-Evans C, Clark D, Jarvis J, Stewart C, O'Brien TD. 2022. Kinetics, kinematics and muscle activation during eccentric squatting. *ISBS Proceedings Archive: Vol. 40: Iss. 1, Article 10*

Armstrong R, Langan-Evans C, Baltzopoulos V, Clark D, Jarvis J, Stewart C, O'Brien TD. 2023. Traditional resistance training may not be enough. Is accentuated-eccentric loading the answer? *European College of Sports Science Conference*

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List of Abbreviations

1RM = One-Repetition Maximum

ANOVA = Analysis of Variance

ASIS = Anterior Superior Iliac Spine

CV = Coefficient of Variation

DOMS = Delayed onset of muscle soreness

EMG = Electromyography

GRF = Ground Reaction Force

IKD = Isokinetic Dynamometer

Kineo = Kineo Training System

MEPs = Motor Evoked Potentials

RPE = rating of perceived exertion

S&C = Strength & Conditioning

SENIAM = Surface Electromyography for the Non-Invasive Assessment of Muscles

TRAD = Traditional

Chapter 1.

General Introduction

1.1 Background

Athletic performance is a result of the interplay between technical skill, tactics, psychological status and physiological factors. Of these physiological factors, the force production of skeletal muscle has been identified as a key performance indicator (Suchomel et al., 2016). For example, in order to achieve greater sprinting velocities, greater ground reaction force (GRF) is required (Weyand et al., 2000), which is enabled by the ability to generate greater forces from the lower limb musculature (Morin et al., 2015). However, the forces that the musculature are able to produce during any given action are highly variable and are a result of both the type of muscle contraction and the velocity at which that contraction occurs (Alcazar et al., 2019).

Skeletal muscle contraction can be defined by three contraction types. Concentric muscle contraction is defined as the generation of force whilst shortening of muscle, eccentric muscle contraction is defined by the generation of force whilst lengthening of muscle, and lastly, isometric muscle contraction is defined as a muscle contraction that results in the generation of force with no change to muscle length (Faulkner, 2003). It has been well established that during ex-vivo muscle contraction that greater maximal forces are produced during eccentric contractions, followed by isometric contractions, and with concentric contractions producing the least amount of force (Hill, 1938, Katz, 1939, Edman, 1988). This relationship is known as the force-velocity relationship, and is also observed in-vivo in single-joint movements (e.g., knee extension/flexion) (Pain and Forrester, 2009), however, there is dearth of research investigating this relationship during the eccentric phase of multi-joint resistance training movements due to the difficulty of assessing maximal eccentric forces, with only one study to date having done so (Hahn et al., 2014).

Due to the presumption that eccentric contractions produce greater forces, as seen during single-joint assessments of the force-velocity relationship (Alcazar et al., 2019), many applied strength and conditioning (S&C) practitioners have adopted specialist eccentric resistance training modalities (Harden et al., 2020a, Suchomel et al., 2019a) in the belief that the forces produced during these eccentric resistance training modalities will be greater than traditional resistance training modalities. Therefore, resulting in superior hypertrophic and strength adaptations, or eccentric-specific adaptations, thus enhancing physiological athletic capabilities.

However, there are several issues with this line of thinking. Firstly, the majority of force-velocity relationship research has been performed on single-joint modalities (Douglas et al., 2017), whereas multi-joint movements are typically utilised with applied practice during S&C training to develop physiological athletic capabilities (e.g., the squatting exercise) (Ratamess et al., 2009). Previous research has established that the neural activity during single-joint and multi-joint movements differ (Behm et al., 2003), and that the opposing segmental dynamics of individual joints during multi-joint actions can cancel each other out (Bobbert, 2012). Considering these factors, and that only one previous study has assessed the multi-joint force-velocity relationship in a resistance-training movement (leg press), and that joint kinetics differ between the squat and leg press (Sjöberg et al., 2021) it is currently not fully known how similar the single-joint force-velocity relationship will be to that of the multi-joint squatting force velocity relationship. .

Secondly, the force-velocity relationship assesses maximal force production which is typically performed under isovelocity conditions. However, in applied practice, force production and movement velocity are variable and are a product of a constant external loading. Thus, even though maximal eccentric force potential might be greater than concentric force, it is unknown if eccentric force production will be greater due to the acceleration effects of gravity acting on the external load. During upwards movements (concentric), gravity acts as an opposing force which must be overcome, whilst during downwards movements (eccentric) gravity acts as an assistive force which can be resisted to varying amounts, and thus the eccentric forces required may not be maximal.

Despite the dearth of research investigating the underpinning mechanics of eccentric resistance training, there is a growing body of research, and applied use, of eccentric resistance training (Douglas et al., 2018, Cook et al., 2013, English et al., 2014, Walker et al., 2016, Harden et al., 2020b), particularly during exercises such as the squat (Douglas et al., 2018). This can be segmented into several subcategories, including; tempo-training, iso-inertial training, and accentuated-eccentric loading (Suchomel et al., 2019a, Suchomel et al., 2019b). Of these modalities, accentuated-eccentric loading appears to be the most promising, with several studies identifying that this method might lead to superior, or at least equal, adaptations to those seen from traditional resistance training in terms of muscular strength, power, and markers of athletic performance (e.g. jumping, sprinting, change of direction) and hypertrophy (Douglas et al., 2018). However, much is still unknown about how to implement accentuated-eccentric loading into applied practice (Harden et al., 2020a), or for the rationale behind why certain eccentric loads are utilised. This thesis will therefore attempt to answer these questions.

1.2 Aims, Objectives and Structure of Thesis

The overall aim of this thesis was to improve our understanding of the underpinning movement dynamics during accentuated-eccentric loading in the squat to inform training prescription, and to identify if such accentuated-eccentric loading could be a viable resistance training methodology in previously strength-trained populations. In order to achieve this, a series of studies were performed by firstly examining the force-velocity relationship of squatting, followed by the movement dynamics and muscle activity during the eccentric phase of the squat. Finally, then utilising this information to develop a training intervention to assess the effectiveness of accentuated-eccentric loading. An overview of these studies is presented in the aims of each chapter below.

The aim of chapter two was to establish the existing knowledge about eccentric resistance training. This was achieved by exploring and reviewing the previous literature examining eccentric muscle contraction, the subsequent movement dynamics during eccentric muscular contractions, and how eccentric resistance training has been incorporated in to applied practice. This knowledge will serve to inform the experimental investigations presented in the remainder of this thesis.

The aim of chapter three was to investigate the capabilities of the Kineo Training System (v7.0, Globus, Italy) and to identify if it could facilitate eccentric strength testing and eccentric resistance training during the squat exercise. This was assessed by establishing the validity and reliability of the isovelocity mode which is required to facilitate force-velocity relationship assessments. Secondly, this was achieved by examining differences in movement dynamics between squats performed on the Kineo and squats performed with a barbell.

The aim of chapter four was to establish the force-velocity relationship during the squatting exercise. This was achieved by utilising concentric and eccentric isovelocity squatting combined with measurements of GRFs.

The aim of chapter five was to determine the movement dynamics and muscle activity during the eccentric phase of squatting across a range of traditional and accentuated-eccentric loads in comparison to the concentric phase of the squat exercise. This data was then used to inform the training intervention programme design and associated outcome measures of chapter six.

The aim of chapter six was to assess the effectiveness of accentuated-eccentric loading during the squat compared to traditional loading. This was facilitated by a six-week training intervention with strength-trained males, and included pre-test/post-test measures of muscular strength, markers of athletic performance, and muscle architecture. The training intervention programme design, and outcome measures were developed by utilising the knowledge gleaned from the previous chapters in this thesis.

Finally, in chapter seven, the findings of the experimental investigations are synthesised regarding their implications on applied practice within the field of S&C, and recommendations are given for future research.

Chapter 2.

Literature Review

2.1 Introduction

The aim of this literature review was to examine previous evidence related to eccentric muscular contractions, with particular reference to the squatting exercise, which is one of the most commonly prescribed resistance training movement patterns (Ratamess et al., 2009). In order to achieve this aim, this chapter will first explore the underpinning mechanisms that underpin muscular contraction and force production. The second part of this chapter will then explore the specific movement dynamics of the squat exercise. This chapter will then finish with an examination of eccentric resistance training methodologies have been utilised in applied practice.

2.2 Ex-Vivo Force-Velocity Relationship

Investigations into the mechanical properties of muscular contraction have been ongoing since the early 20th century. Many of these early studies examined the mechanical properties of muscle removed from small animals, and thus examined ex-vivo. The ex-vivo muscle would be artificially stimulated, allowing for the quantification of maximal forces and velocities during muscular contractions. The relationship between the forces produced and the associated velocities at which these were measured was thusly name the force-velocity relationship.

The first of these ex-vivo studies appeared to be undertaken in the 1920's and 1930's (Gasser and Hill, 1924, Fenn and Marsh, 1935), which investigated the effects of concentric velocity on the muscular force produced in frog sartorius muscle. However, it is the work of Hill (1938) in the late 1930's which is more commonly cited as the first foray into understanding the force-velocity relationship. This seminal work by Hill (1938) resulted in the hyperbolic curve that is typically still used today to represent the force-velocity relationship during concentric muscular contraction (Alcazar et al., 2019) (Figure 2-1). However, there were limitations in exploring the eccentric force-velocity relationship, with Hill noting that they could only stimulate the muscle to contract against loads that were marginally greater than those used to elicit an isometric contraction due to the experimental setup, and thus only low eccentric velocities could be utilised.

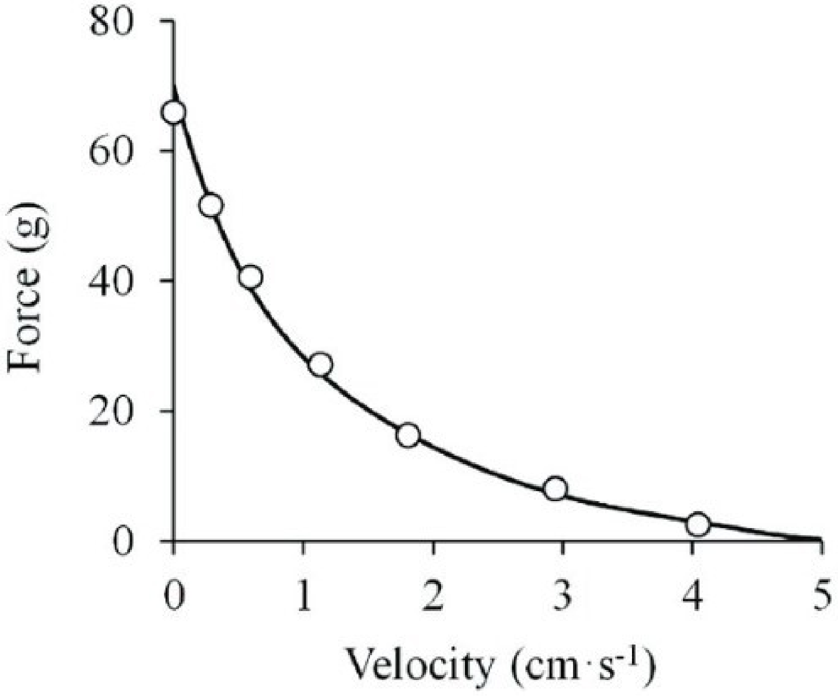

Figure 2-1 Depiction of the concentric ex-vivo force-velocity relationship. Recreation of data from Hill (1938). Taken from Alcazar (2019)

Katz (1939) followed up Hills' work with an ex-vivo investigation of the eccentric portion of the force-velocity relationship and identified several key findings. Firstly, the velocity at which a muscle eccentrically contracts to a given load were smaller than those suggested by the equations put forth by Hill (1938), this resulted in reports of substantially greater eccentric forces. Secondly, an eccentric contraction against a load 1.9 times greater than those used to elicit an isometric contraction would exceed the mechanical properties of the muscle to contract, thus leading to the appearance of muscular relaxation, due to mechanical failure. Lastly, loads that were greater than isometric, but smaller than the mechanical failure point resulted in a sudden initial lengthening of the muscle followed by a uniform lengthening of the muscle (Katz, 1939). This study enabled the early depiction of the eccentric portion of the force-velocity relationship, demonstrating the sudden rise in eccentric force at low eccentric velocities, before appearing to plateau. However, it was Edman (1988) who explored this relationship in greater detail utilising single muscle fibres. Edman's (1988) research suggested that the concentric relationship was not in fact hyperbolic, but rather sigmoidal and that peak eccentric forces were approximately 1.8 times that of the isometric force (Figure 2-2).

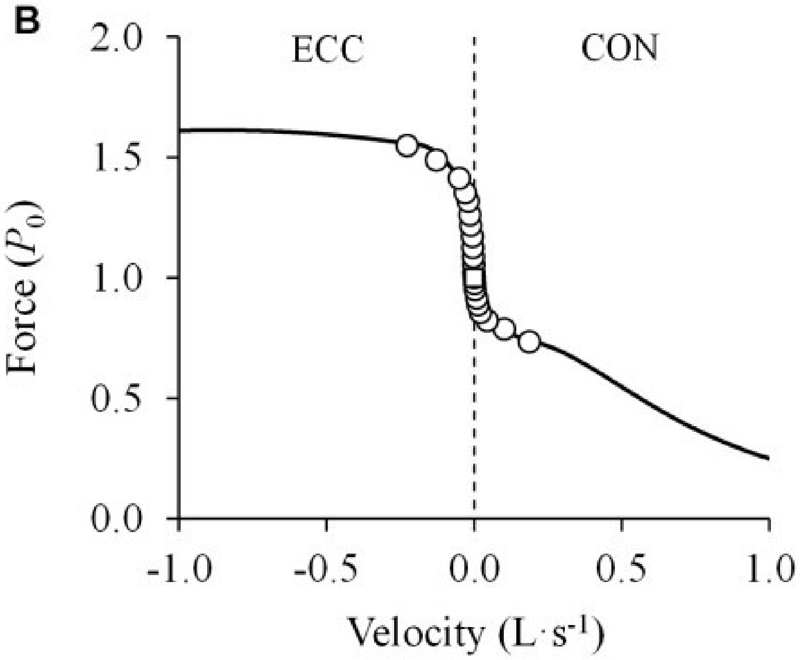

Figure 2-2 Depictions of the ex-vivo force-velocity relationship. Recreation of the data presented in Edman (1988). Taken from Alcazar (2019)

Taken together, the works of Hill (1938), Katz (1939) and Edman (1988) describe the inherent link between maximum available force and contraction velocity, and confirm that greater forces can be produced during eccentric muscular contraction than concentric contraction, with maximal ex-vivo eccentric force being between 1.8 to 1.9 times greater than the isometric force.

The shape of the concentric portion of the ex-vivo force-velocity relationship can be explained in part by cross-bridge kinetics and the relationship between the attachment /detachment rate of cross-bridges at a given velocity, the change in cross-bridge force at a given velocity, and the change in sarcomere shortening distance per myosin motor stroke at a given velocity (Piazzesi et al., 2007, Seow, 2013) It is worth noting however that the shape of the concentric portion of the force-velocity relationship in isolated muscle fibres was also influenced by the myosin heavy chain isoform, with faster twitch fibres being less hyperbolic than slower twitch fibres (Bottinelli et al., 1996), thusly the amount of force that can be produced per cross-bridge decrease as velocity increases, resulting in a curvilinear shape in the concentric portion of the force-velocity relationship.

Several theories have attempted to explain why greater forces can be produced during eccentric muscular contractions, including; the cross-bridge theory, the sarcomere length non-uniformity theory, and the passive element theory (Herzog, 2018b). The cross-bridge theory (Huxley, 1957) is based on the assumption that all cross-bridges have the same force producing capabilities. The mathematical formulation to explain this was able to accurately predicted both concentric (Huxley, 1957) and isometric (Gordon et al., 1966) force production, however Herzog *et al.,* (2015) noted that the eccentric force calculated from these equations are not accurate. Therefore, other factors must also play a role. One suggested factor is that the myosin extension that binds to actin consists of an elastic region (Adamovic et al., 2008), therefore the greater the stretch on the myosin extension (i.e., during eccentric contraction) the greater the force production. Secondly, the myosin S1 head is capable of rotating through several positions, thus changing the tension expressed on the actin filament (Huxley and Simmons, 1971, Rayment et al., 1993). Therefore, these two structural elements allow a greater force to be produced during the eccentric contraction, due to an increased tension between the actin & myosin filaments.

The sarcomere length non-uniformity theory (Morgan, 1990) postulates that muscular force is regulated by the length of the sarcomere (Gordon et al., 1966). At short sarcomere lengths, the double overlap between actin & myosin prevents full cross bridge formation, so it is only as the sarcomere lengthens to the plateau region of the force-length curve, that optimal cross bridge formation can occur (Gordon et al., 1966). As the sarcomere continues to lengthen, two things may happen; firstly, the number of active myosin-actin cross bridges decline, secondly some (weaker) sarcomeres may ‘pop’ before a myosin-actin cross bridge can be reformed (Morgan, 1990). This re-formation of a crossbridge was theorised to cause a non-uniform sarcomere length between sarcomeres (Allinger et al., 1996), thus altering the tension within the muscle fibre. However, based on the force-length relationship, it should only be possible for the forces produced during eccentric contraction to equal the isometric maximum force at optimal sarcomere length. Despite this, several studies have shown that during lengthening, sarcomeres can produce forces greater than the isometric forces produced at optimal sarcomere length (Herzog and Leonard, 2002, Rassier et al., 2003). Therefore, the sarcomere length non-uniformity theory alone cannot explain the increased force production during eccentric contraction.

To overcome the limitations of the two previously mentioned theories, the passive element theory has been proposed. This theory is based on the research that suggests that an elastic component exists, which allows for additional tension to be developed within the sarcomere (Edman et al., 1978). Herzog (2018a) suggests that the myofibril protein titin is the primary mechanism that allows for this passive increase in force during eccentric contractions. Titin, which was previously known as connectin (Maruyama, 1976), is an elastic spring-like protein which connects the M-Line & Z-Line of a sarcomere. Current evidence suggests that titin can modulate the stiffness/tension of the sarcomere, and thus causes a passive increase in force production during eccentric contraction. The mechanisms by which titin modulates sarcomere stiffness is not fully understood, however, several possible solutions have been proposed including; titin phosphorylation (Anderson et al., 2010), titin-actin binding (Leonard and Herzog, 2010), and titin activation via Ca^{2+} (Cornachione et al., 2016). Currently, the passive element theory provides the most likely solution for why eccentric muscle contraction is able to produce greater forces ex-vivo (Herzog, 2018b).

2.3 In-Vivo Force Velocity Relationship

2.3.1 Single Joint

Following the investigations in to the ex-vivo force-velocity relationship, the next stage of force-velocity research investigated this relationship in-vivo. Investigations into the force-velocity relationship in humans can be broadly split in to two areas, single-joint movements and multi-joint movements. As with the ex-vivo research, early studies predominantly focused on the concentric muscle action (Hill, 1922). However, it was not until the early 70's that utilisation of isokinetic dynamometers allowed the measurement of the eccentric portion of the force-velocity relationships (Komi, 1973) (Figure 2-3), or rather as it should be referred to the moment-velocity relationship. This allowed for the measurement of maximal joint moments, at defined angular velocities. One of the first studies to explore the moment-velocity relationship demonstrated that the maximum elbow extensor moments during eccentric contractions were only 1.2 to 1.3 times greater than the isometric joint moment (Komi, 1973). These values were significantly smaller than the 1.8 times isometric found ex-vivo (Edman, 1988). Many other research groups explored the eccentric moment-velocity relationship for other human joints including; knee extensors/flexors (Dudley et al., 1990, Melo et al., 2016, Pain and Forrester, 2009, Perrine and Edgerton, 1978, Amiridis et al., 1996, Westing et al., 1990, Evangelidis et al., 2016), hip extensors (Boling et al., 2009), ankle dorsi- and plantar-flexors (Connelly and Vandervoort, 2000, Liederbach and Hiebert, 1997), and elbow flexors (Hortobágyi and Katch, 1990). All the aforementioned studies produced a similar range of eccentric joint moments (1.0 to 1.3) relative to isometric (Alcazar et al., 2019). As with the ex-vivo measurements, a rapid increase in the measured eccentric joint moment was observed during each increase in eccentric velocity, with eccentric force then plateauing as velocity continued to increase (Komi, 1973).

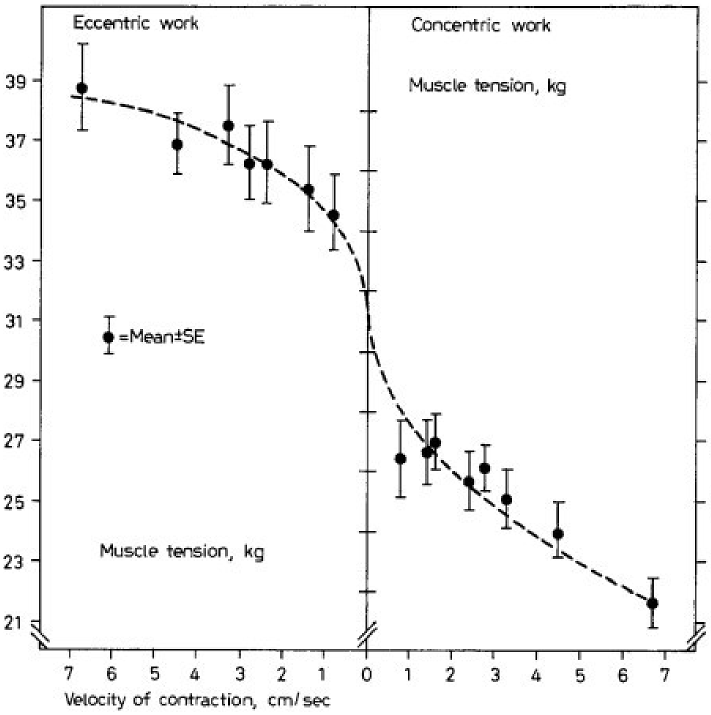

Figure 2-3 Depiction of the in-vivo force-velocity relationship. Taken from Komi (1973)

In efforts to explain why the eccentric joint moments (relative to isometric) were significantly smaller in-vivo than the ex-vivo eccentric forces (relative to isometric), several mechanisms have been suggested, including; the influence of muscle-tendon interactions (Roberts and Azizi, 2010), moment arms (Lieber and Boakes, 1988), the type of exercise (and musculature involved) (Hollander et al., 2007), and sex (Hollander et al., 2007). However, the most prevailing mechanism that has been suggested is the neural control of eccentric contractions, which may influence the ability to produce maximal eccentric joint moments in-vivo (Perrine and Edgerton, 1978, Westing et al., 1988, Hortobágyi and Katch, 1990).

Dudley *et al.,* (1990) tested this hypothesis and utilised artificial electrical stimulation of the vastus lateralis and vastus medialis muscles to investigate if muscle activation was a limiting factor in eccentric joint moment production. It was found that voluntary contractions of the knee extensors produce eccentric joint moments of approximately 1.05 to 1.1 times isometric. However, when the vastus lateralis and medialis were artificially stimulated during muscular contraction, the knee extensors produced joint moments of 1.4 to 1.5 times that of isometric. Westing *et al.,* (1990) found similar results with artificial stimulation increasing eccentric joint moments by 24%. Pain and Forrester (2009) also demonstrated that electromyography (EMG) amplitude during voluntary eccentric contractions was ~20-30% smaller than during isometric contractions. Pain and Forrester (2009) then utilised computational modelling to demonstrate that when an eccentric joint moment was corrected by accounting for muscle activity, eccentric joint moments could theoretically increase by approximately 60%, and would thus be in line with the expected forces during ex-vivo eccentric contractions. Taken together, these studies show that there is some level of neural inhibition preventing maximum joint moments being produced during the eccentric muscle contraction in-vivo. However, it is worth noting that strength-trained individuals typically have a lower level of eccentric neural inhibition than that of untrained populations (Aagaard, 2018). It was noted by Amiridis et al. (1996) that strength-trained populations have lower levels of co-activation than untrained populations during maximal concentric and eccentric knee extensor tasks. Therefore, in order to limit the effects of neural inhibition, research investigating maximal eccentric forces should be assessed in strength-trained populations.

Several mechanisms have been suggested for the eccentric neural inhibition. Research has shown that during eccentric contraction, the muscle may only be able to reach a voluntary activation level of ~75-90% compared to ~90-95% during isometric contraction (Babault et al., 2001, Beltman et al., 2004). Furthermore, motor unit discharge rate (rate-coding) is ~30% lower during eccentric contractions than during concentric or isometric contractions (Del Valle and Thomas, 2005), this remains true even after taking into account the difference in EMG between the contraction types.

Previously, it was believed that the difference in the neural activation during eccentric contraction was regulated via Ib afferent negative feedback (i.e., Golgi-Tendon organ), however, recent research does not support this during eccentric contractions (Duclay et al., 2014). Rather, it appears that this reduction is regulated by spinal & supra-spinal mechanisms (Duchateau and Baudry, 2014, Duchateau and Enoka, 2016). Howatson *et al.,* (2011) used transcranial magnetic stimulation to measure cortical excitability during eccentric and concentric muscular contraction. Greater cortical excitability occurred during maximal & sub-maximal eccentric contractions than during concentric contraction (Howatson et al., 2011), although this may vary depending on joint angle (Doguet et al., 2017). Research by Fang *et al.,* (2004) has also shown higher cortical activation amplitudes, particularly during the latter stages of an eccentric movement, as well as a greater area of the brain being activated, during eccentric than during concentric contraction (Fang et al., 2004). Taken together, these studies indicate that the supra-spinal control of muscular contraction also varies between eccentric and concentric muscular contractions.

In addition to supra-spinal mechanisms, it has been suggested that eccentric muscular contraction is also regulated at the spinal level. Gruber *et al.,* (2009) examined the motor evoked potentials (MEPs) & cervicomedullary MEPs during concentric and eccentric contractions and found that cervicomedullary MEPs were ~28% lower during maximal eccentric contractions than during concentric contractions. However, the MEPs to cervicomedullary MEPs ratio was greater during eccentric than concentric, therefore suggesting that a reduced spinal excitability and increased supra-spinal excitability, which further supports the findings of Howatson *et al.* (2011) and Fang *et al.,* (2004).

In addition, Duclay *et al.* (2005) suggests a pre-synaptic Ia afferent (muscle spindle) inhibition occurs during eccentric contraction. Whilst post-synaptic recurrent inhibition (via Renshaw cells) is greater during eccentric contractions than during concentric or isometric contractions (Barrue-Belou et al., 2018), this may explain the lower discharge rate found by others (Del Valle and Thomas, 2005). Taken together, these studies further signify a differing neural control that is dependent on contraction type. Combined, these spinal and supra-spinal mechanisms help to explain why a decreased muscle activity is observed during eccentric contractions and may be why the eccentric phase of the in-vivo moment-velocity profile is lower than the expected ex-vivo force-velocity profile.

2.3.2 Multi-Joint

Although a wide body of research has investigated the single-joint in-vivo force(moment)-velocity relationship, there is a dearth of research that has adequately researched the eccentric phase of the multi-joint in-vivo force-velocity relationship. When it comes to lower body multi-joint actions several measurement modalities are available; squatting (Rahmani et al., 2001, Orange et al., 2020), leg press (Bosco et al., 1995, Hahn et al., 2014), jumping (Feeney et al., 2016) and cycling (Rudsits et al., 2018, Dorel et al., 2005, Driss et al., 2002). Typically GRFs or pedal torque were measured/calculated (rather than the individual joint moments).. The majority of this research has only been able to establish the concentric portion of the force-velocity relationship. One of the first studies to do so Bosco et al. (1995) used an infrared sensor to measure vertical displacement and thus calculate velocity and acceleration, and thus allowing forces to be calculated when mass is known. This technology would develop into the more commonly available linear-position transducers such as those used in applied practice to assess the force-velocity relationship (de Lacey et al., 2014).

However, Rahmani *et al.* (2001) was able to directly measure forces utilising force-plates and then calculate velocity allowing for the comparison of these measures when produced during squats with incremental external loads. Despite only being able to measure the concentric phase in the aforementioned studies, one key finding did emerge. The concentric force-velocity relationship appears to be more quasi-linear rather than the hyperbolic/sigmoidal relationship seen during single-joint assessment. Through musculoskeletal modelling (Bobbert, 2012) it has been shown that the individual joint moments during a multi-joint task are hyperbolic/sigmoidal, however the opposing segmental dynamics of each lower limb segment during synchronistic hip and knee extension cancel each other, thus resulting in a quasi-linear relationship . Despite this, the eccentric phase of the multi-joint force-velocity relationship was still unknown.

One of the primary reasons for why assessment of the eccentric phase is complex, is due to the inherent difficulty in applying maximal eccentric loads to participants during multi-joint movements. The muscular effort required to control the eccentric phase of a given external load increases as the hip and knee joints flex (Bryanton et al., 2012), resulting in a variable velocity throughout the range of motion (Miletello et al., 2009). This therefore results in peak GRF and joint moments occurring in mechanically disadvantageous positions (Thompson et al., 2023, Choe et al., 2021), leading to an underestimation of maximum eccentric force capabilities.

Despite this, several studies have attempted to investigate the eccentric phase of the force-velocity relationship during the squat, however, these in fact only measured eccentric force characteristics. McNeil *et al.,* (2021) examined eccentric forces during several difference loads and measured subsequent velocities. However, participants in this study were told to maximise eccentric velocity (i.e., perform the eccentric phase as quickly as possible), which combined with the negative acceleration of gravity resulted in submaximal eccentric forces, and thus was an inaccurate depiction of the force-velocity relationship. Conversely, Frohm *et al.,* (2007) did instruct their participants to maximally resit a supramaximal load during the eccentric phase whilst squatting, and thus could define their measurements as maximal voluntary eccentric forces. However, this was only done at a singular velocity (0.11 m·s^{-1}) and no comparison was made to maximal concentric forces, and therefore a force-velocity relationship could not be developed. To date, only one previous study has accurately measured the multi-joint force-velocity relationship. Hahn *et al.,* (2014) used a motor-driven leg press which allowed for the participants to maximally resist eccentric loads across a range of velocities. The results of Hahn *et al.* (2014) indicate that peak the eccentric forces produced during in-vivo multi-joint movements are approximately 1.15 times that of isometric force (see Figure 2-4). Although this is slightly smaller than the magnitude seen in the single-joint force-velocity relationship, the shape of the relationship is similar, with an initial rise in eccentric force as velocity increases before a plateau and decline phase.

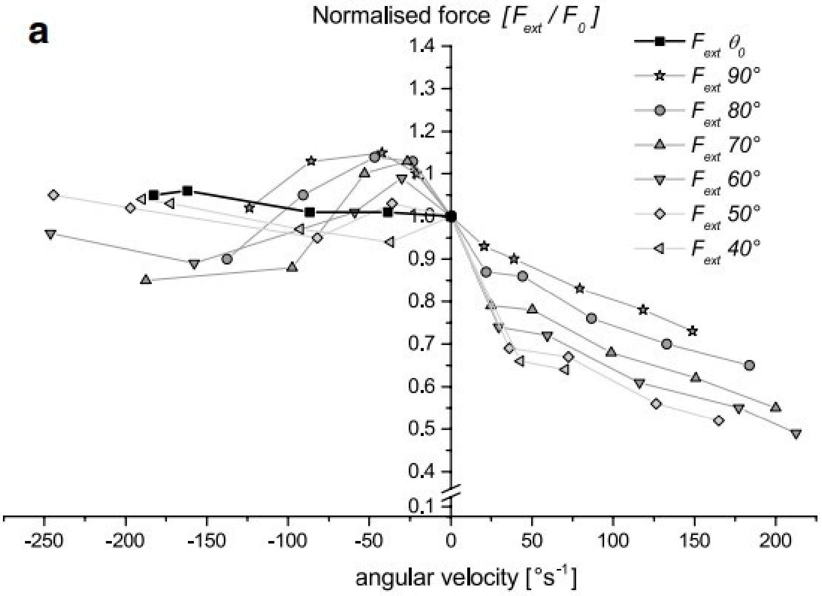

Figure 2-4 Depiction of the multi-joint in-vivo force-velocity relationship during the leg press exercise. Taken from Hahn (2014)

Taken together, these studies indicate that the concentric phase of the multi-joint force-velocity relationship is well established and is quasi-linear in nature. However, due to the dearth of research investigating the eccentric phase, it is not well known what the maximal capabilities of the skeletal muscle are during multi-joint movements.

2.4 Length-Tension Relationship

In addition to the force-velocity relationship, the force production capabilities of muscle are also mediated by the length of the muscle fibre (Gordon et al., 1966). Known as the length-tension relationship, this change in force production at different lengths can be attributed to the number of actin-myosin cross-bridges formed. At short muscle fibre lengths, also known as the ascending arm, the double overlap between actin & myosin prevents full cross-bridge formation and thus maximal force production is attenuated. As the muscle fibre lengthens, a greater number of actin-myosin cross-bridges can be formed, with maximal force occurring with optimal cross-bridge formation (Gordon et al., 1966). As the muscle fibre continues to lengthen, also known as the descending limb, the number of actin-myosin cross-bridges declines due to a lack of overlap, and thus force production declines.

This relationship has also been observed in single joint actions, and is thusly named the torque(moment)-angle relationship. During measures of isometric knee extension moment, joint moments were observed to peak at 80°, with a decrease in moment as joint angle increased (longer muscle length) and decreased (shorter muscle length) (Marginson and Eston, 2001). It also appears that the type of contraction appears to affect the angle at which peak force is expressed (Melo et al., 2016), with peak eccentric moments occurring at greater knee joint angle (longer muscle lengths) compared to concentric moments.

Examination of this relationship is made more complex in multi-joint actions owing to the combination of differing joint angles, and thus muscle lengths, possible at a given centre of mass height (Brady et al., 2020). However, there is evidence to suggest that this relationship exists in multi-joint movements such as the deadlift, with (Beckham et al., 2012) reporting ground reaction forces being the lowest when the isometric action was performed at ankle height (long muscle length), and forces increasing as the barbell position was transitioned to knee height, and then peak forces occurring at mid-thigh height. However, as the muscle continued to shorten and the barbell was placed at hip heigh, ground reaction forces once again decreased, signifying the presence to the descending and ascending arms of the force-tension relationship. Similar findings have been reported during an isometric squat with greater ground reaction forces being reported at a knee joint angle of 30° than at 60° and 90° (Palmer et al., 2018b). This is of particular interest as peak ground reaction forces during a dynamic squat occur at greater knee joint angles (e.g. 110°) (Choe et al., 2018) suggesting that the forces produced in mechanically disadvantaged positions (i.e. long muscle lengths) are a determining factor in successful completion of a squat rather than the absolute peak force that can be produced. No previous literature has examined the squat under isovelocity conditions, so it is unsure if the peak ground reaction forces will be affected by the dynamic constraints of the length-tension relationship to a similar manner as reported in single-joint modalities (Melo et al., 2016), and thus it is unsure at what centre of mass height isometric squats will need to be performed for normalisation of squatting forces during force-velocity relationship assessments.

2.5 Movement Dynamics and Muscle Activity During Squatting

This first section of this literature review described the force-velocity relationships as seen during ex-vivo muscle contraction, and in-vivo in both single-joint and multi-joint movements. However, the force-velocity relationship is only one component of movement dynamics. The following section of this literature review will focus on the joint kinematics, kinetics, and muscle activity that are presented during the squatting exercise. This therefore allows for identification of potential gaps within the literature, which can then be examined in the later chapters of this thesis.

2.5.1 Squat Kinematics

The squat can be characterised by the following movement sequence; 1) standing upright with the hips and knee joint fully extending and ankle joints in a neutral position, 2) the synchronistic flexion of the hip and knee joints in the sagittal plane which result in the lowering of the centre of mass (eccentric phase), 3) the synchronistic extension of the hip and knee joint in the sagittal plane raising the centre of mass until returning to the start position (concentric phase) (Schoenfeld, 2010b). Appleby *et al.,* (2019) has demonstrated that weighted squats (with loads ranging from 70% to 90% of one-repetition maximum (1RM)) typically result in a centre of mass average velocity of ~0.6 to 0.4 $m \cdot s^{-1}$ and peak velocities of ~1.3 to 1.1 $m \cdot s^{-1}$ during the concentric phase, however these values may drop to 0.2 $m \cdot s^{-1}$ and 0.8 $m \cdot s^{-1}$ for mean and peak velocities respectively during a 1RM (Banyard et al., 2017, Kasovic et al., 2019). In order to achieve a parallel squat position (defined as the top of the thighs parallel to the ground), the centre of mass is typically displaced by ~0.6 m in adult males (Thompson et al., 2023). In terms of joint kinematics, in order to achieve the parallel squat position, the knee typically flexes by ~120 to 130° and hip by ~90 to 100°, whilst the ankle would dorsi-flex by 25 to 35° (Choe et al., 2021, Krzyszkowski and Kipp, 2020). In regards to the trunk, Diggin *et al.,* (2011) demonstrated that the trunk would anteriorly incline as approaching the parallel squat position, resulting in a trunk angle of ~30° in relationship to the ground. This allows for the centre of mass to be maintained over the base of support (midfoot) throughout the entirety of the squat. Similar findings for the knee, hip, ankle, and trunk were all reported by Swinton *et al*., (2012) during high-bar squatting. However, if a low-bar squatting position is performed, hip flexion range of motion may increase, with a decrease in knee joint range of motion. In terms of joint velocities, average joint velocities for the knee and hip range from ~90 to 150 $^{\circ} \cdot s^{-1}$, whilst peak joint velocities can range from ~200 to 450 $^{\circ} \cdot s^{-1}$ depending upon external load (Kellis et al., 2005).

2.5.2 Squat Kinetics

During the concentric phase of the squat, peak GRFs have been reported to range between ~22.6 to ~32 N·kg^{-1} (Kellis et al., 2005, Swinton et al., 2012) depending upon external load. Analysis of the force-time traces by Thompson *et al.,* (2023) during squatting identified two peaks in GRF, the first peak occurred during the transition between the eccentric and concentric phase in order to overcome the inertia of the external load, a second (albeit smaller) peak occurs at ~80% of the way through the concentric phase (Thompson et al., 2023). Choe *et al.,* (2021) reported similar wave form patterns for both the hip and knee extensor moments during squatting, with peak extensor moments occurring at the start of the concentric phase. Several studies have shown that hip and knee extensor joint moments are typically in the range of ~2 to ~3 Nm·kg^{-1}, dependent upon external load (Swinton et al., 2012, Choe et al., 2021, Krzyszkowski and Kipp, 2020), whilst the ankle plantar-flexors would typically produce ~0.7 to ~1 Nm·kg^{-1}.

An interesting observation reported by Flanagan and Salem (2008) was that an increase in external load results in an increase in hip and knee joint moments. However, these increases were not to the same magnitude. At light loads (e.g., 20% 1RM), both the hip and knee moments contributed ~45% each to the sum of joint moments, however at heavier loads (e.g., 80% 1RM), the relative contributions of the knee extensors decreased to ~30% whilst the hip extensors contribution ~60% to the sum of joint moments, suggesting that at higher loads the hip extensors are responsible for the further increases in GRF. However, this finding is not always supported, for example Swinton *et al*., (2012) found that the hip extensor contributions remained at ~45% regardless of external loading. As both studies used strength-trained individuals, it is unclear exactly why these findings differ. One possible explanation could be due to squatting technique deficiencies during the concentric phase. In some populations, as load increases the hips may rise faster than that the shoulder girdle, causing the trunk to incline and thus increasing the moment arm around the hips (Myer et al., 2014). This would therefore require a greater hip extensor joint moment, and could explain the differences between the two aforementioned studies (Swinton et al., 2012, Flanagan and Salem, 2008).

During the squat it has also been suggested that maximal joint moments cannot be produced. Bryanton *et al.,* (2012) compared the hip and knee extensor joint moments during the concentric phase of squatting to maximal joint moments produced during single-joint maximal voluntary contractions on an isokinetic dynamometer. The findings from this study suggest that during squatting, the knee extensors produce a joint moment of ~60% of their maximum voluntary contraction and hip extensor joint moment of ~70%. This deficit is likely due to the greater degrees of freedom in the squat, which can decrease the muscle activity (Behm et al., 2003), increase the joint instability (Wuebbenhorst and Zschorlich, 2011) and subsequently decreases the ability to generate force (Maffiuletti et al., 2016, Wuebbenhorst and Zschorlich, 2012).

2.5.3 Muscle Activity

Studies investigating the muscle activity during the squat have consistently shown that the majority of the lower limb musculature are active (Robertson et al., 2008, Mehls et al., 2022) as are the erector spinae (Gullett et al., 2009) and abdominal muscles (Joseph et al., 2020, Clark et al., 2019). Multiple factors can influence the magnitude of muscle activity, with Pereira *et al.,* (2010) showing that as squat depth increases, quadricep muscle activity increases. Similar findings were also found for the gluteus muscles (Caterisano et al., 2002). There also exists a clear relationship between the external load and muscle activity, with increases in load resulting in increased muscle activity (albeit non-linearly) (van den Tillaar et al., 2019). However, not all muscle activity is of the same magnitude. Gullet *et al.,* (2009) has shown that quadricep muscle activity is typically greater than hamstring activity. Likewise, Yavuz *et al*., (2015) has shown that in the concentric phase the quadricep and gluteus muscle have similar and greater muscle activity, than the hamstrings. It has been shown that vastus lateralis and gastrocnemius activity is typically greatest at the start of the concentric phase, whilst the gluteus maximus activity typically peaks around 80% of the way through the concentric phase (Robertson et al., 2008), whilst the hamstring activity remained fairly consistent throughout (Robertson et al., 2008). These muscle activity patterns seem to sync with the peaks in GRFs, suggesting that the quadriceps are key for initiating the concentric phase.

2.5.4 Movement Dynamics and Muscle Activity During the Eccentric Phase

Unfortunately, although there is an extensive amount of research specifically targeting the concentric phase of the squat, there is limited discussion within the literature regarding the eccentric phase. This may be due to the concentric phase of the squat being the limiting factor in successfully completing a squat (Choe et al., 2021), thus making it more appealing to report the concentric data and not the eccentric data. Looking at literature that did include the eccentric phase in their analyses, Swinton *et al.,* (2012) reported that lower GRFs occurred during the eccentric phase of the squat which was also accompanied by lower velocities compared to the concentric phase. Similar results were also reported by Comfort *et al.,* (2015) showing the GRFs during the eccentric phase of a squat variation were ~10% lower than the concentric phase.

In terms of muscle activity, several studies have reported reduced levels of muscle activity in both the lower limbs (Gullett et al., 2009) (~20 to 45% decrease) and trunk musculature (Clark et al., 2019) (~30 to 50% decrease) during the eccentric phase. Cabral *et al.,* (2023) also reported that muscle activity for the vastus lateralis and gluteus maximus were ~ 30% and ~50% lower, respectively, during the eccentric phase than during the concentric phase. However, as the magnitude of difference was greater in the gluteus maximus than the vastus lateralis, this suggests that the knee extensors are preferentially recruited during the eccentric phase of the squat.

Based on the above, and comparing to the concentric data, it becomes apparent that there is a lack of research into the eccentric phase of the squat. Therefore, one of the primary aims of this thesis will be to explore the kinetics, kinematics and muscle activity during the squat, with a particular reference to the eccentric phase in relation to the concentric phase.

2.6 Eccentric resistance Training Methodologies

Resistance training has been demonstrated to increase muscle strength via changes in muscle morphology and muscle activity (Folland and Williams, 2007) and to induce hypertrophic adaptations to the trained musculature (Abe et al., 2000). Manipulating the manner in which resistance training is performed can lead to additional specific adaptations (Tillin and Folland, 2014). Mata-analyses have identified that performing maximal eccentric-only contractions and concentric-only contractions results in similar improvements in concentric strength and isometric strength, however, greater improvements were found in eccentric strength for those who performed eccentric actions (Roig et al., 2009). These eccentric specific improvements in strength have been suggested to be velocity specific, with improvements in high velocity joint moments requiring specific training at high velocities (Paddon-Jones et al., 2001).

Due to the literature suggesting that eccentric muscular contractions can lead to equivalent improvements in concentric and isometric strength, whilst eliciting superior improvements in eccentric strength many applied S&C coaches have begun to utilise training methodologies that attempt to modify the dynamic loading of the eccentric phase of a movement (Suchomel et al., 2019a). Due to the lack of availability of specialised training devices, such as isokinetic dynamometers which enable maximal eccentric contractions to occur, and the recommendations to use free-weight resistance training exercises (e.g. the squat) in applied practice (Ratamess et al., 2009) strength and conditioning coaches have sought other alternatives than enable them to maximise the forces produced during the eccentric phase of an exercise. Several methods have been suggested, such as increasing the tempo/duration of the eccentric phase, or by altering the load used during the eccentric phase compared to the concentric phase. These methods are referred to as eccentric tempo training and accentuated-eccentric loading, respectively (Suchomel et al., 2019a).

2.6.1 Eccentric Tempo Training

Despite its use within applied practice, several studies have suggested that eccentric tempo training may be inferior to traditional resistance training due to the subsequent loss in concentric force and velocity (van den Tillaar, 2019), and thus power (Pryor et al., 2011) on the following concentric repetition, which could then attenuate the potential training stimuli (Lacerda et al., 2016). Meta-analyses have highlighted that purposely performing long eccentric tempo offers no benefit over performing traditional duration eccentric tempos (Schoenfeld et al., 2015). For example, Shibata *et al.,* (2021) compared the effects of performing squats with a long eccentric tempo of four seconds vs a traditional eccentric tempo of two seconds, and found significantly greater improvements in squat 1RM occurred from squats performed with a two second tempo (~19%), than with a four second tempo (~10%).

2.6.2 Accentuated-Eccentric Loading

On the other hand, there is some emerging evidence (albeit limited) suggesting that accentuated-eccentric loading may produce superior results than traditional resistance training. This evidence will be discussed throughout the remained of this chapter.

Accentuated-eccentric loading can be defined as any exercise whereby the external load during the eccentric phase is greater than the external load during the concentric phase, whilst minimising any changes in normal movement technique for that exercise (Suchomel et al., 2019a). Broadly speaking, accentuated-eccentric loading can use a wide range of eccentric loads such as performing compound resistance training exercises with ~150% of concentric maximum (English et al., 2014), to performing plyometrics with an additional load of 20% of body mass during the eccentric phase (Godwin et al., 2021). As long as the external loading during the eccentric phase is greater than the concentric phase, an exercise can be classified as using accentuated-eccentric loading. In order to facilitate accentuated-eccentric loading, several methods can be utilised, these can include; weight-release hooks which reduce the concentric load after the completion of the eccentric phase (Munger et al., 2017), manually releasing weights after completion of the eccentric phase (Godwin et al., 2021), pneumatic assistance during the concentric phase (Douglas et al., 2018), pneumatic loading during the eccentric phase, that is then removed for the concentric phase (Harden et al., 2020b), utilising two limbs to lift the load during the concentric phase, but only one limb during the eccentric phase (Mike et al., 2015), or with the use of motorised resistance machine that can automatically alter loading during the concentric and eccentric phase (Sarto et al., 2020). For the purpose of this literature review, the focus will be on accentuated-eccentric loading as used during compound resistance training exercises, and not accentuated-eccentric loading during plyometrics, since the focus of this thesis was to develop the current knowledge base of accentuated-eccentric loading for the purpose of maximising muscular strength, which is achieved through progressive resistance training with heavy loads, rather than plyometric training (Schoenfeld et al., 2021).

As mentioned previously in section 2.4.3, during traditional resistance training (i.e., same absolute external load during both the concentric and eccentric phase), muscle activity is lower by ~20 to 45% in the eccentric phase than during the concentric phase (Gullett et al., 2009). However, Sarto *et al.,* (2020) has demonstrated that training with accentuated-eccentric loading can mitigate this difference, with an accentuated-eccentric load of 150% of 1RM increasing eccentric muscle activity of the vastus lateralis by ~30%. Likewise, Harden *et al.,* (2018a) has demonstrated that accentuated-eccentric loading can significantly increase eccentric GRF by ~25%. Additionally, there is evidence suggesting that performing the eccentric phase with accentuated-eccentric loading can influence performance during the concentric phase, with Munger *et al.,* (2017) reporting significant increases in concentric velocity (~7%) and concentric peak power (~10%) during squats performed with an accentuated-eccentric load of 120% and concentric load of 90%. Taken together, these studies suggest that training with accentuated-eccentric loading may provide a potent training stimulus by augmenting both concentric and eccentric output.

2.6.3 Chronic Adaptations to Accentuated-Eccentric Loading on Muscular Strength

Several studies have also investigated the chronic adaptations to accentuated-eccentric loading, and have shown that this method is superior to, or at least equal to, traditional resistance training in terms of muscular strength development. English *et al.,* (2014) compared the effects of eight weeks of training with accentuated-eccentric load of 110% 1RM to traditional loading with an eccentric load of 80% 1RM. Both groups increased their respective 1RM by ~20% and ~13% respectively. Likewise, Douglas *et al.,* (2018) demonstrated that training with an accentuated-eccentric load of 105% 1RM over eight weeks resulted in a ~5% increase in 1RM whilst traditional training did not elicit any improvements in the same time frame on strength-trained individuals. Cook *et al.,* (2013) also utilised strength-trained individuals and found a ~6% increase in squat 1RM following accentuated-eccentric loading training, with no significant improvements in squat 1RM following traditional resistance training. However, not all studies are in agreement with these findings. Toien *et al.,* (2018) compared the effects of accentuated-eccentric loading at 150% of 1RM to traditional loading in an untrained population and found that both groups improved their 1RM equally. Initially, it might be considered that an accentuated-eccentric load of 150% was too great to recover from, however, Yarrow *et al.,* (2008) and Fisher *et al.,* (2016) both investigated the effects of an accentuated-eccentric load of 100% 1RM against traditional training with externals loads of 60-75% in untrained populations, with both studies finding no significant differences in the improvements in 1RM between traditional and accentuated-eccentric loading resistance training. Collectively, these studies suggest that in strength-trained populations accentuated-eccentric loading can elicit superior improvements in 1RM, however, in untrained populations both accentuated-eccentric loading and traditional resistance training elicit similar improvements in 1RM.

In addition to improvements in 1RM, accentuated-eccentric loading has been shown to improve isolated concentric and eccentric performance. Of particular interest, Walker *et al.,* (2016) investigated the effects of ten weeks of accentuated-eccentric loading against traditional resistance training, and assessed the improvements in single-joint concentric and eccentric knee extensor joint moments. Both groups improved their concentric knee joint moments by ~10%, however only the accentuated-eccentric loading group displayed an increase in their eccentric joint moments (~10%). Likewise, Harden *et al.,* (2020b) demonstrated that accentuated-eccentric loading training resulted in a 11% increase in maximal eccentric leg press GRF. Together, these studies suggest that accentuated-eccentric loading, but not traditional resistance training can elicit eccentric specific strength adaptations. It has been suggested by Walker *et al.,* (2016) that the primary mechanism of these eccentric specific adaptations are predominantly driven by neural adaptations due to the higher muscle activity in the eccentric post-test (Walker et al., 2016).

2.6.4 Chronic Adaptations to Accentuated Eccentric Loading on Athletic Performance

As accentuated-eccentric loading appears to elicit superior strength adaptations than traditional resistance training, it may be presumed that accentuated-eccentric loading would also elicit improvements in markers of athletic performance, due to the correlations between maximal strength and measures of performance in these metrics (Suchomel et al., 2016). However, this is not supported by the current literature for either; jump squat peak power (Horwath et al., 2019), countermovement jump height (Komsis et al., 2014), cycling peak power (Douglas et al., 2018), or sprint performance (Douglas et al., 2018, Cook et al., 2013), with accentuated-eccentric loading resulting in the same magnitude of change as traditional loading. One study did report improvements in countermovement jump peak power (Cook et al., 2013), however participants in this study also performed countermovement jumps as part of the training programme. Due to this limitation, accentuated-eccentric loading alone may not induce athletic performance adaptations.

However, there is some emerging evidence to suggest that accentuated-eccentric loading may have an impact on reactive strength properties, with Papadopoulos *et al.,* (2014) reporting an increase in drop jump power, whilst decreasing ground contact time by ~17%. Douglas *et al.,* (2018) also investigated the effects of accentuated-eccentric loading on drop jump performance, however their findings were unclear on whether accentuated-eccentric loading positively influenced drop jump performance due to the small effect sizes. Given this, more research is needed to identify if accentuated-eccentric loading may prove beneficial for markers of athletic performance.

2.6.5 Chronic Adaptations to Accentuated Eccentric Loading on Muscle Hypertrophy

Due to the greater external loads during accentuated-eccentric loading and subsequent forces produced (Harden et al., 2018a), there is a potential for an increase in mechanical tension, which is a key mechanism for eliciting hypertrophy (Wackerhage et al., 2018). However, only a small number of studies have assessed hypertrophy as a result of accentuated-eccentric loading, and there is debate in the literature whether accentuated-eccentric loading is superior to traditional resistance training in this matter. Several studies have demonstrated that both accentuated-eccentric loading and traditional resistance training elicit similar changes in; muscle cross sectional area as assessed by magnetic resonance imaging (Brandenburg and Docherty, 2002, Friedmann-Bette et al., 2010), or muscle thickness assessed by ultrasonography (Walker et al., 2016, Douglas et al., 2018). However, other studies have observed a greater increase in vastus lateralis fascicle length following accentuated-eccentric loading compared to traditional resistance training (Walker et al., 2020), as well as an increase in type 2x fibre cross sectional area (Friedmann-Bette et al., 2010). Due to the limited research on this topic, and the short duration of these interventions, it is currently unknown if accentuated-eccentric loading is superior to traditional resistance training in terms of hypertrophic adaptations. What limited evidence that does exist, seems to suggest that accentuated-eccentric loading does not negatively affect hypertrophic adaptations, and may cause more subtle changes. Combined, this evidence further supports the suggestion of Walker *et al.,* (2016) that the superior strength adaptations that result from accentuated-eccentric loading are primarily due to neural adaptations in the short term, rather than changes in muscle architecture.

Despite the potential positive adaptations, many S&C practitioners are cautious of including accentuated-eccentric loading within their training repertoire due to the perception of increased muscle damage, delayed onset of muscle soreness (DOMS), and ratings of perceived exertion (RPE) (Harden et al., 2020a). Merrigan and Jones (2021) have demonstrated that an acute bout of accentuated-eccentric loading resulted in greater DOMS than traditional training. Likewise Yarrow *et al*., (2007) reported higher RPEs and blood lactate levels following accentuated-eccentric loading in untrained individuals. However, in strength-trained populations RPE was similar for accentuated-eccentric loading and traditional resistance training (Merrigan et al., 2021). Additionally it appears that RPE can be attenuated following several bouts of accentuated-eccentric loading in untrained populations (Yarrow et al., 2008). Therefore, these studies suggests that the perceived negative impacts of accentuated-eccentric loading may be due to either a) training status, or b) the unfamiliarity with the training stimuli.

2.6.6 Future Directions for Accentuated-Eccentric Loading

Considering all the literature in terms of chronic adaptations and negative effects of accentuated-eccentric loading, it appears that accentuated-eccentric loading may only be beneficial for specific populations. Only in strength-trained populations did accentuated-eccentric loading appear to elicit superior strength adaptations than traditional resistance training (Douglas et al., 2018, Cook et al., 2013, Harden et al., 2020b, Walker et al., 2016), which may be due to greater levels of muscle activity (Aagaard, 2018). On the other hand, in untrained populations accentuated-eccentric loading was only equal to traditional resistance training (Toien et al., 2018, Yarrow et al., 2008, Fisher et al., 2016), whilst also displaying greater DOMS and RPE (Merrigan and Jones, 2021, Yarrow et al., 2007). Therefore, future research should focus accentuated-eccentric loading research in strength-trained populations.

However, in all the discussed literature, no scientific justifications were given for why specific accentuated-eccentric loads were selected, which is in contrast to traditional resistance training methodologies which are well documents and justified by decades of research (Ratamess et al., 2009). Furthermore, there has been a notable interest within the S&C community for a better understanding of the selection of accentuated-eccentric loading protocols (Harden et al., 2020a). Therefore, future training intervention research should be based upon scientifically justified loading recommendations that are developed by understanding the underpinning movements dynamics and muscle activity during accentuated-eccentric loading.

2.7 Conclusion

This literature review has examined the underpinning mechanics that influence eccentric resistance training with particular reference to the squat exercise. From the literature, it is apparent that accentuated-eccentric loading is of particular interest for applied practice. However, many questions still remain on how best to utilise this training methodology. Firstly, it is unclear what the maximum capabilities of eccentric force production are during squatting, and to what extent force is produced under accentuated-eccentric loading conditions. Understanding these in greater detail will be the purpose of chapters four and five. Secondly, further research is required to understand the adaptations from accentuated-eccentric loading, this should be assessed in strength-trained males, given that this population that appears to have a greater benefit from this training methodology, this will be examined in chapter six.

Chapter 3.

Technical Considerations of the Kineo Training System for Squatting and Eccentric Loading

3.1 Abstract

Introduction The Kineo System is a motorised resistance machine that facilitates resistance training exercises such as a squat under a variety of loading conditions. No previous research has investigated the Kineo. Therefore, the aim of this chapter was to compare the movement dynamics of squats performed on the Kineo to squats performed with a barbell. Secondly, to assess the validity and reliability of the isovelocity mode.

Methods Fifteen male participants (23 ± 2 years, 85 ± 6.5 kg, 183 ± 4 cm) performed isovelocity squatting at three concentric (0.25, 0.5, & 0.75 $m.sec^{-1}$) and three eccentric velocities (-0.25, -0.5, & -0.75 $m.sec^{-1}$), during which the instantaneous cable velocity of the Kineo was recorded to assess the reliability and validity of the isovelocity mode. Participants also performed assessments for 1RM and load-velocity profiling to identify strength and movement velocity capabilities of Kineo squatting in comparison to barbell back squatting. Finally, movements kinematics and muscle activity of the lower limbs were identified during the Kineo squat, barbell back squat, and barbell front squat.

Results Excellent agreement was found between measured and prescribed isovelcoities with an intraclass correlation coefficient of 0.99 (95% CI of 0.96 to 0.99). Bland-Altman analysis identified a bias of ~0.01 $m{\cdot}s^{-1}$ greater than the prescribed velocity. Barbell squat 1RM was greater than Kineo squat, however squat velocity was equivalent when loading was at 80% 1RM. Hip, knee, and ankle kinematics were similar for all 3 squat variations, however the Kineo squat has a significantly smaller range of motion. Gluteus maximus EMG was similar for all squat variants, however greater vastus lateralis activity was found in the Kineo squat and barbell front squat than the Barbell back squat.

Conclusion The findings of these studies suggest that the isovelocity mode of the Kineo is fit for purpose, and is valid and reliable. Comparisons of the Kineo squat to the barbell back squat

and barbell front squat suggest that any future data will be replicable of a squatting action, with the Kineo squat more similar to the barbell front squat than the barbell back squat.

3.2 Introduction

One of the major challenges in studying whether accentuated-eccentric loading could be a viable resistance training methodology is the availability of appropriate equipment required to facilitate manipulations of the eccentric phase of the squat. As described within the literature review in chapter two, there are several methods by which this can be achieved including; weight-release hooks (Munger et al., 2017), dropping of weights after completion of the eccentric phase (Godwin et al., 2021), pneumatic assistance during the concentric phase (Douglas et al., 2018), pneumatic loading during the eccentric phase, (Harden et al., 2020b), the two:one method (Mike et al., 2015), or with the use of motorised resistance machine that can automatically alter loading during the concentric and eccentric phase (Sarto et al., 2020). The subsequent studies that were undertaken during this PhD programme, utilised a commercially available motorised resistance machine known as the Kineo Training System (Kineo).

The Kineo is a motorised resistance machine that facilitates multi-joint closed chain exercises such as the squat. A cable pulley system is attached to the participant which protrudes from underneath a platform which is then connected to the Kineo motor (Figure 3-2). The motor is controlled by an in-built computer, which regulates the motor-torque throughout the prescribed exercise and is displayed to the investigator as the equivalent mass under normal gravitational conditions.

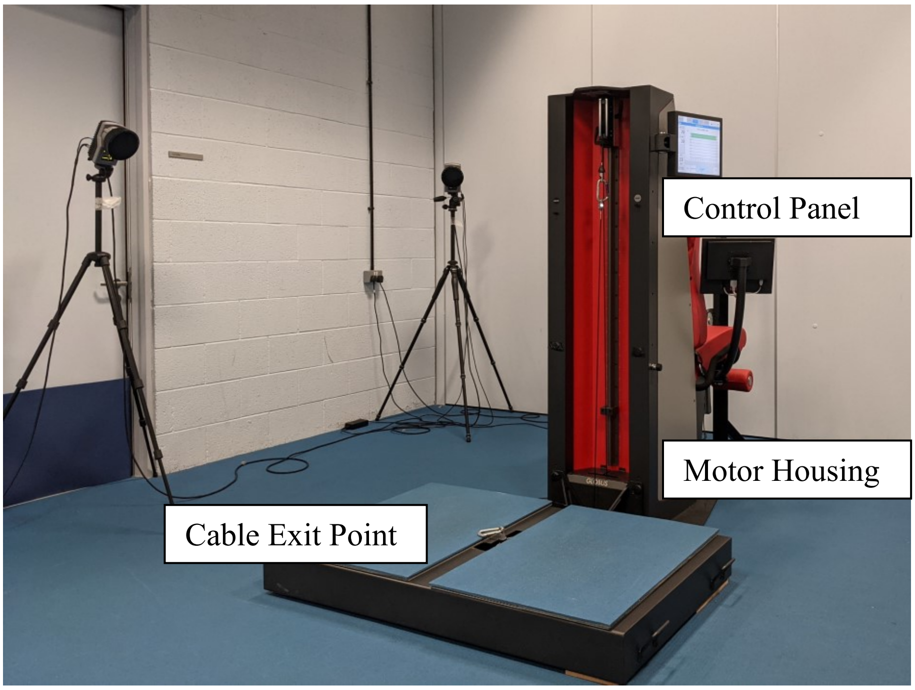

Figure 3-1 Kineo Training System, with labels indicating the location of the Kineo control panel, the motor housing, and the exit point of the cable which is subsequently attached to the participant

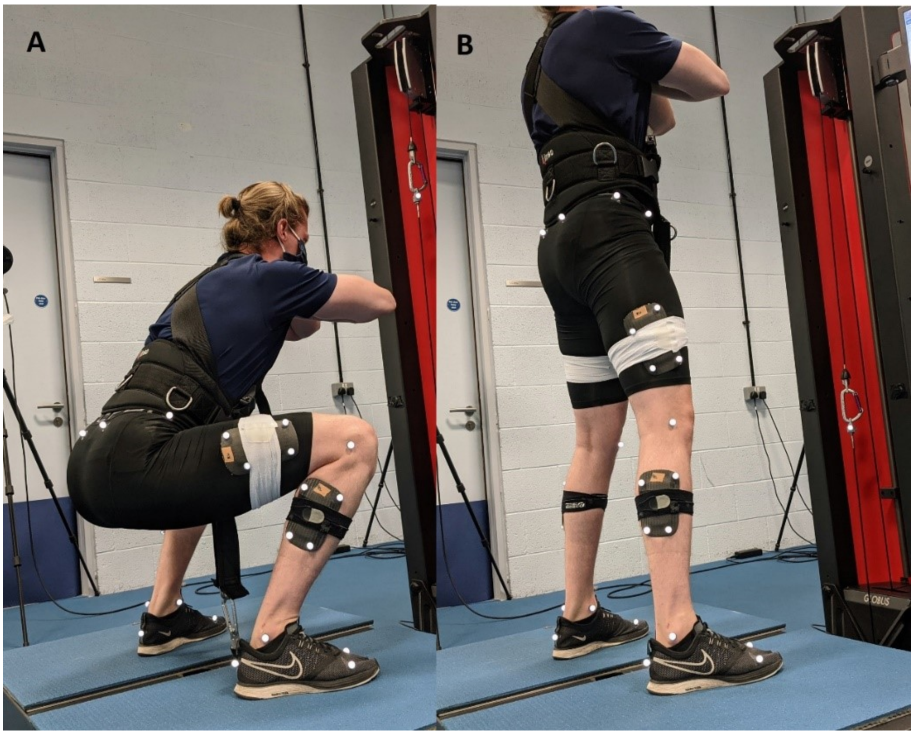

Figure 3-2 Set up for the Kineo training system. With a participant demonstrating the Kineo squat to a parallel thigh position

In order to perform a squat on the Kineo, the participant wears a hip/shoulder harness. The harness is tightened over the shoulder and around the waist. A length of webbing protrudes from the anterior hip portion of the harness which can then be connected to the cable pulley system. The participant then aligns themselves by standing above the cable exit point on the Kineo platform, so that the cable line of action is in a vertical path and in line with the midfoot. A range of motion test is then performed, whereby the cable displacement is measured and stored on the Kineo computer to determine the position of the start of the eccentric phase, the end of the eccentric phase, the start of the concentric phase, and the end of the concentric phase. These values will then facilitate automatic load changes for the concentric and eccentric phase of the squat.

Several modes of operation exist in the Kineo software, however the main two of interest are the isovelocity mode, and the ‘isotonic mode’ which replicates the resistance profile of a free-weight exercise (constant external load throughout the range of motion). The isovelocity mode makes it possible to assess maximal forces by applying loading during specific movement velocities, and thus allowing the exploration of the maximum strength capabilities and force-velocity relationship. Whilst the ‘isotonic mode’ would enable the depiction of movements dynamics that are similar to those seen during free-weight exercises (such as the barbell squat), which are more commonly used in applied practice.

It is well established that the forces produced during eccentric ex-vivo muscular contractions (Edman, 1988) and the moments produced during maximal in-vivo single-joint movements (Komi, 1973) are greater than those seen during either isometric or concentric (Alcazar et al., 2019). However, as mentioned in chapter two, there is an inherent difficulty in assessing the maximum forces during the multi-joint movements such as the squat.

In order to accurately assess maximum forces during squatting, measurements of force production would have to be performed under isovelocity conditions, as suggested by Hahn *et al.,* (2014). This is the method typically utilised when assessing maximum single-joint movements (Alcazar et al., 2019). The isovelocity mode of the Kineo is therefore of particular interest, due to this mode potentially facilitating the exploration of the multi-joint force-velocity relationship, which would allow for the identification of maximal eccentric forces in-vivo. It is important that the reliability and validity of the isovelocity mode is identified, to ensure that it is fit for purpose, before assessments of the multi-joint force-velocity relationship are performed. Owing to the motor driven aspect of the Kineo, this study will test if it is possible to perform squats under isovelocity conditions, by automatically regulating the external load delivered by the Kineo's motor.

The squat exercise is one of the primary resistance training exercises used in applied practice, in part because the movement dynamics (kinetics, kinematics and muscle activity) have been extensively studied, and that squatting subsequently loads the musculature used in during athletic tasks (i.e. lower limbs and trunk) (Ratamess et al., 2009). Thusly, this is why the barbell squat is often considered the gold-standard for assessing lower body strength outside of a laboratory (McMaster et al., 2014). However, prior to this thesis, no data existed on the movement dynamics of squats performed on the Kineo. In order for the data presented in this thesis to be applicable as an equivalent alternative in applied practice, the movement dynamics of squats performed on the Kineo should be similar to those performed with a barbell.

There are several types of movement dynamics that would be of particular interest in order to compare the Kineo squat to a barbell squat. These include comparisons to external loading capabilities, such as the maximum loads that can be lifted, and the velocities at which sub-maximal loads can be lifted (load-velocity profile). However, it is also important to assess whether the movement kinematics of the Kineo squat are different to those seen during the barbell squat, as kinematics can vary between squat variations (Swinton et al., 2012), which can subsequently lead to differing performance adaptations (Rhea et al., 2016, Pallarés et al., 2020). Evidence suggests that the positioning of the external load (i.e. posteriorly during the barbell back squat, anteriorly during the barbell front squat) may alter muscle activity of the lower limbs ((Gullett et al., 2009, Yavuz et al., 2015), therefore due to the positioning go the loading with the Kineo squat (anteriorly loaded), it will be important to assesses load capabilities and

Therefore, in order to assess the ecological validity of the Kineo squat, it will be important to understand the loads lifted, the velocity produced, the joint kinematics, and the muscle activity of the Kineo squat and how this may differ to barbell squatting, and if the Kineo squat more closely resembles a barbell back squat or barbell front squat.

The first objective of this study was to assess the reliability and validity of the Kineo isovelocity function across a range of velocities in both the concentric and eccentric phase of a squat. The second objective of this study was to compare the maximum loads capable of being lifted during barbell squats and squats performed on the Kineo, and to compare the velocities at which sub-maximal loads are lifted (load-velocity profile). The third objective of this study was to compare the squat kinematics and muscle activity during the Kineo squat to two commonly performed free weight squat variations (barbell back squat and barbell front squat).

3.3 Methodology

Participants: Fifteen strength-trained males (23 ± 2 years, 85 ± 6.5 kg, 183 ± 4 cm) who were familiar with the barbell squat volunteered for this study. All participants were free of musculoskeletal injuries and could demonstrate correct squatting technique as determined by an experienced and qualified S&C coach (National Strength and Conditioning Association accredited). Participants were informed of the study procedures and gave written informed consent. This study was ethically approved by the Liverpool John Moores University research ethics committee. All 15 participants completed objective 1 and 2, whilst only 12 participants were able to complete objective 3 at a later date.

Experimental Protocol: Participants reported to the Liverpool John Moores laboratories on seven occasions (two familiarisation sessions, and five experimental testing sessions). The first and second experimental testing sessions involved performing a 1RM squat assessment for the Kineo squat and barbell back squat, respectively. Whilst the third and fourth experimental testing sessions were used to identify the load-velocity profile of the Kineo and barbell back squat, respectively. Finally, the fifth experimental testing day was used to assess the reliability and validity of the Kineo isovelocity function. Once laboratory access was regranted following the COVID-19 pandemic, 12 participants reported again to the Liverpool John Moores University laboratories on three further occasions (two familiarisation sessions, and one experimental testing session). Experimental testing was used to assess the kinematics and muscle activity during the Kineo squat, the barbell back squat, and barbell front squat.

During each session, participants underwent a standardised warmup following the RAMP protocol (Jeffreys, 2006), which included five minutes of cycling on a cycle ergometer (Wattbike, England), followed by dynamic whole body movements. For more details on this warmup, please refer to the appendices section.

During the initial two familiarisation sessions, participants were introduced to the Kineo on which they would perform the experimental testing on. Participants were fitted with the hip/shoulder harness, which was adjusted for goodness of fit. Squat stance was standardised with feet shoulder-width apart and externally rotated by ~20°. Squatting range of motion was determined, whereby the eccentric phase started with the participant standing with hips and knees fully extended and lasted until the participant had squatted down to a depth where the top of the thigh was parallel to the ground. The concentric phase began after the eccentric phase finished and until the participant had fully extended the hips and knees, and was standing upright. Participants then performed several progressively heavier sets through a full range of motion to become familiarised with squatting on the Kineo. Loading was increased until the participant reported a rating of perceived exertion (RPE) that corresponded to a value of nine out of ten (Zourdos et al., 2016). Participants would then perform three repetitions of squats at the following velocities in a randomised order; 0.75 $m{\cdot}s^{-1}$, 0.5 $m{\cdot}s^{-1}$, 0.25 $m{\cdot}s^{-1}$, -0.25 $m{\cdot}s^{-1}$, -0.5 $m{\cdot}s^{-1}$, -0.75 $m{\cdot}s^{-1}$ (whereby a positive velocity indicates a concentric squat, and negative velocity indicates an eccentric squat). These velocities were chosen because they encapsulate the range of velocities typically seen during 1RM squatting attempts (0.25 $m{\cdot}s^{-1}$ (Banyard et al., 2017)) and the upper limit of what the Kineo is designed to achieve in the eccentric phase (-0.75 $m{\cdot}s^{-1}$). Five minutes of passive rest was given between each trial, with 30 seconds between each repetition. During concentric squats, participants were instructed to perform the concentric phase with maximum effort, whilst during the eccentric squat participants were instructed to produced maximum effort to resist the downwards pull of the motor.

The same familiarisation process was performed during the additional familiarisation sessions that was completed by the returning 12 participants, with the exception of the squatting performed under isovelocity conditions. During these familiarisation sessions, participants were asked to demonstrate correct squatting technique in the barbell back squat, and the barbell front squat.

Squat One-Repetition Maximum: During the first experimental testing day, after participants' body mass and height were collected (SECA 704/202, Germany) and following the standardised RAMP warmup, participants completed a 1RM squat assessment on the Kineo. After a minimum of 72 hours rest, participants reported for the second experimental testing day in which they completed a 1RM back squat assessment with the barbell. 1RM assessments for both the Kineo squat and barbell back squat were performed in accordance to the guidelines set out by the National Strength and Conditioning Association (Haff and Triplett, 2015). In brief, participants were instructed to perform several progressively heavier sets of squats up until achieving 90% of their predicted 1RM, afterwards the participants would have a maximum of five attempts to achieve a 1RM. The highest load that was successfully lifted through a full range of motion was used for analysis.

Load-Velocity Profile: During the third and fourth experimental testing days, participants performed the standardised warmup and then performed a load-velocity profiling assessment for the Kineo squat and barbell back squat, respectively. In order to perform the load-velocity profile, participants performed three repetitions at 20%, 40%, 60%, and 80% of their respective 1RM, with instructions to squat with a full range of motion and to perform the concentric phase as quickly as possible. Mean movement velocity was recorded using a linear position transducer (GymAware, Australia). The greatest recorded mean velocity from the three repetitions was used for analysis.

Isovelocity squatting: During the fifth experimental testing day, participants performed three repetitions of isovelocity squats at the following velocities in a randomised order; 0.75 $m \cdot s^{-1}$, 0.5 $m \cdot s^{-1}$, 0.25 $m \cdot s^{-1}$, -0.25 $m \cdot s^{-1}$, -0.5 $m \cdot s^{-1}$, -0.75 $m \cdot s^{-1}$, adhering to the technique performed in the familiarisation. A reflective marker was placed on the Kineo cable and was tracked with three 3D motion tracking cameras (Opus 3 series, Qualisys, Sweden) sampling at 200 Hz. Data were recorded in Qualisys Track Manager (Qualisys, Sweden) and then exported to Visual3D (C-Motion, USA) for data analysis. From each repetition of each trial, instantaneous vertical velocity was calculated and the isovelocity phase identified (Figure 3-3).

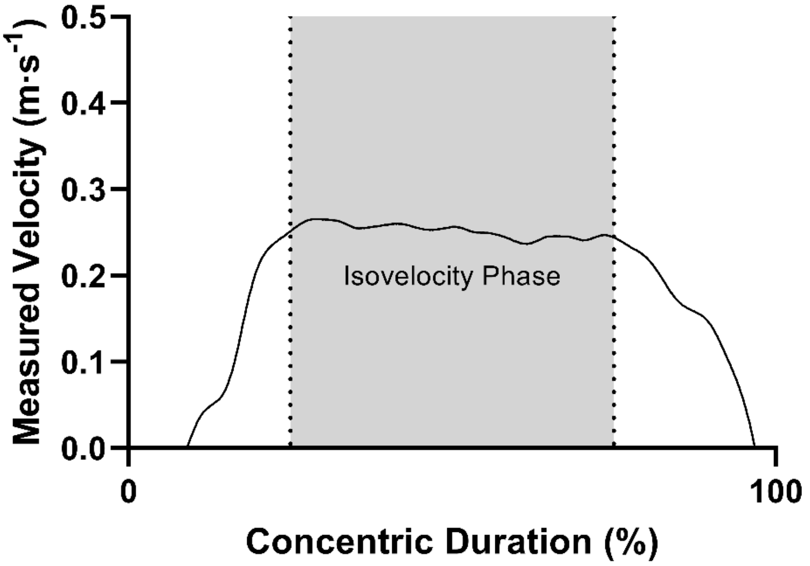

Figure 3-3 Example of the measured velocity (m·s^{-1}) during a concentric trial with a prescribed velocity of 0.25 (m·s^{-1}).

Squat Kinematics and Muscle Activity: Participants were fitted with surface EMG electrodes (BlueSensor, Ambu, Denmark), and reflective markers. Before electrode placement, the skin over the vastus lateralis and gluteus maximus was shaved, abraded, and cleaned with an isopropyl alcohol swab (70%) to improve signal clarity. EMG electrodes were positioned following the recommendations of the SENIAM project (Hermens et al., 1999). To allow normalisation of EMG signals, participants performed a maximal isometric voluntary contraction for the knee extensors in a seated position with the knee flexed at 80°, and maximal isometric voluntary contraction of the hip extensors in a prone position with the hip flexed at 30° (0° represent full extension for both hip and knee joints). EMG signals from experimental trials were normalised against these isometric values.

A 36-marker set utilising technical and anatomical markers were used to track kinematics of the pelvis and lower limbs. This included a modified CODA pelvis marker set (additional tracking markers located on the iliac crest) to account for ASIS occlusion during hip flexion. The remaining markers tracked the thigh, shank, and feet segments (lateral & medial femoral epicondyles, lateral & medial malleoli, heel, 1st & 5th metatarsals, thigh cluster, & shank cluster). Functional joint analyses were performed to calculate the hip and knee joint centres utilising the Gilette algorithm (Schwartz and Rozumalski, 2005).

Pelvic tilt angle was determined with respect to the global coordinate system (Lewis et al., 2015), with a positive angle representing anterior pelvic tilt, and negative angle representing posterior pelvic tilt about the mediolateral axis. This results in an anterior pelvic tilt angle of ~10° when standing upright (Lewis et al., 2017). Hip angle was determined from the thigh segment in relation to the pelvis rotating about the determined functional hip joint centre. Knee angle was determined from the shank segment in relation to the thigh segment rotating about the determined functional knee joint axis, with an angle of 0° representing full hip and knee extension, respectively. Ankle angle was determined from the foot segment in relation to the shank segment, rotating about the mediolateral axis. An ankle angle of 0° represents a neutral ankle position when standing upright, with a positive joint angle representing ankle dorsiflexion.

Participants performed the Kineo squat, barbell back squat, and barbell front squat variation in a randomised order. For each variation, three repetitions were performed at 50%, 85%, and 100% of body mass. Each trial was separated by three to five minutes of passive recovery.

Electromyography signals were wirelessly transmitted (Research DTS, Noraxon, USA) (sampling at 1500 Hz) to a desktop computer. A six camera, 3D-motion capture system (Opus 3 series, Qualisys, Sweden) (sampling at 200 Hz), was used to track the reflective markers. Motion and EMG data were collected synchronously in Qualisys Track Manager (Qualisys, Sweden) and then exported to Visual 3D (C-Motion, USA) to undergo analyses. Motion data were lowpass filtered (4th order Butterworth) with a 6 Hz cut-off frequency. EMG data were processed via a 10-250 Hz band pass filter, before a root mean squared moving average of 100 ms. Motion data allowed for quantification of peak joint angle (°), range of motion (°), and joint velocity ($°\cdot s^{-1}$), and the electromyography data allowed for quantification of muscle activity, normalised to isometric maximum (%).

Statistical analysis: All data was analysed in SPSS (v27, IBM, USA) and were normally distributed (Shaprio-Wilk test > 0.05). Therefore, to achieve objective one, the mean velocity during the isovelocity period from each repetition (henceforth known as 'measured velocity') was used to identify within trial coefficient of variation in order to assess reliability, and intraclass correlation coefficient in order to assess the extent of agreement between the measured velocity and prescribed velocity. The mean velocity of the isovelocity period of each repetition was then compared to the prescribed velocity via Bland-Altman analyses (with limits of agreement) to assess the validity of the prescribed velocity from the Kineo. To achieve objective two, comparisons between the barbell back squat and Kineo squat were statistically analysed using a repeated measures paired samples t-test. To achieve objective three, a two-way repeated measures ANOVA, with Bonferroni post-hoc analysis (squat variation x squat load) was used to assess whether the squat variation and/or load influenced squatting kinematics/muscle activity. Effect sizes were calculated for all ANOVA's that displayed significance tests using omega-squared (ω^2), with values of 0.01, 0.06, and 0.14 indicating a small, medium and large effect size, respectively (Field, 2013). Coefficient of variation (%) was used to identify intra-trial reliability. All data are reported as mean ± SD.

3.1 Results

Barbell back squat 1RM was significantly greater (120 ± 13 kg) than the Kineo squat 1RM (110 ± 13 kg) ($t_{14} = 6.883$, $P < 0.001$, 95% CI = 7.11 – 13.55) (Figure 3-4). Likewise, the concentric velocity at 20% 1RM, 40% 1RM, and 60% 1RM was significantly greater on squats performed with the barbell back squat, than the Kineo squat ($t_{14} = 4.001$, $P < 0.001$, 95% CI = 0.06 – 0.2; $t_{14} = 2.779$, $P = 0.015$, 95% CI = 0.03 – 0.23; $t_{14} = 2.837$, $P = 0.13$, 95% CI = 0.02

– 0.17). However, there was no significant difference between barbell back squat velocity (0.58 m·s^{-1}) and Kineo squat velocity (0.52 m·s^{-1}) when assessed at 80% 1RM ($t_{14} = 1.903$, $P = 0.078$, 95% CI = -0.007 – 0.13) (Figure 3-4).

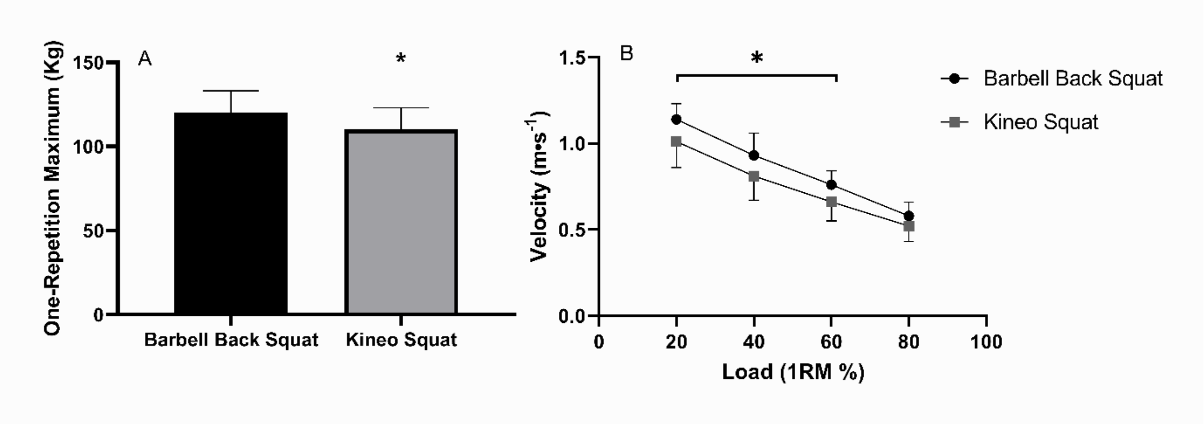

*Figure 3-4 Mean ± SD one-repetition maximum (n = 15) (A) and load-velocity profiles (B) for the barbell back squat and Kineo squat. * Indicates a significant difference (P < 0.05) between the squat variations.*

When assessing the Kineo isovelocity function, repetition to repetition coefficient of variation ranged from 1.6% to 4% across all six velocities, with the greatest variation being during 0.25 m·s^{-1} and -0.25 m·s^{-1} trials. This resulted in a standard deviation of ~0.01 m·s^{-1} during the isovelocity phase for each velocity, therefore suggesting that the velocities produced by the Kineo are reliability.

Agreement of measurements between the prescribed velocity and measured velocity during concentric isovelocity squat produced an intraclass correlation coefficient of 0.99 with 95% CI of 0.97 to 0.99. Likewise, during the eccentric isovelocity squats, the intraclass correlation coefficient was 0.99 with 95% CI of 0.96 to 0.99, suggesting excellent agreement between the measured and prescribed isovelocities. Bland-Altman analyses (Figure 3-5) revealed that measured concentric velocity was on average ~0.01 m·s^{-1} greater than the prescribed velocity ($P < 0.001$, limits of agreement = -0.007:0.029). Likewise, measured eccentric velocity was on average ~-0.01 m·s^{-1} greater than the prescribed velocity ($P < 0.001$, limits of agreement = -0.029:0.005). Measured isovelocities (mean ± SD) for each prescribed velocity are as follows; 0.76 ± 0.01 m·s^{-1}, 0.51 ± 0.01 m·s^{-1}, 0.26 ± 0.01 m·s^{-1}, -0.26 ± 0.01 m·s^{-1}, -0.51 ± 0.01 m·s^{-1}, and -0.77 ± 0.01 m·s^{-1}.

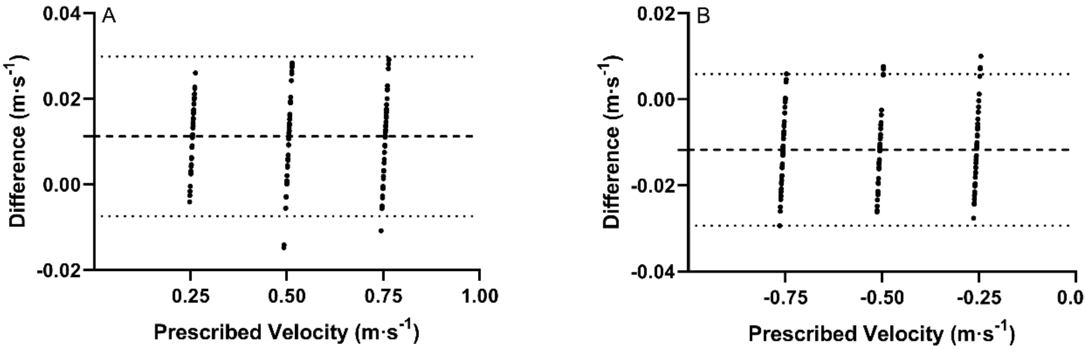

Figure 3-5 Bland-Altman analysis with limits of agreement for the concentric isovelocity trials (A), and for the eccentric isovelocity trials (B). Horizontal dashed line is representative of the mean difference between the prescribed and measured velocity. Horizontal dotted line is representative of ± 1.96 SD.

When comparing squatting kinematics between the three squat variations, there was no significant effect of squatting variation on the range of motion for the hip (76 ± 9°) (F = 0.338, P = 0.719), knee (123 ± 9°) (F = 3.365, P = 0.109), or ankle joints (35 ± 3°) (F = 1.295, P = 0.281). However, there was a medium effect of squatting variation on pelvis range of motion (F = 4.127, P = 0.039, $\omega^2 = 0.08$), with the Kineo squat (11 ± 8°) having a significantly smaller pelvic range of motion than both the barbell back squat (21 ± 6°) and barbell front squat (20 ± 5°) (Figure 3-6). External load had no effect on joint range of motion (P = 0.090-0.754). Therefore, all subsequent discussion of joint ranges of motion refers to the 100% of body mass trial.

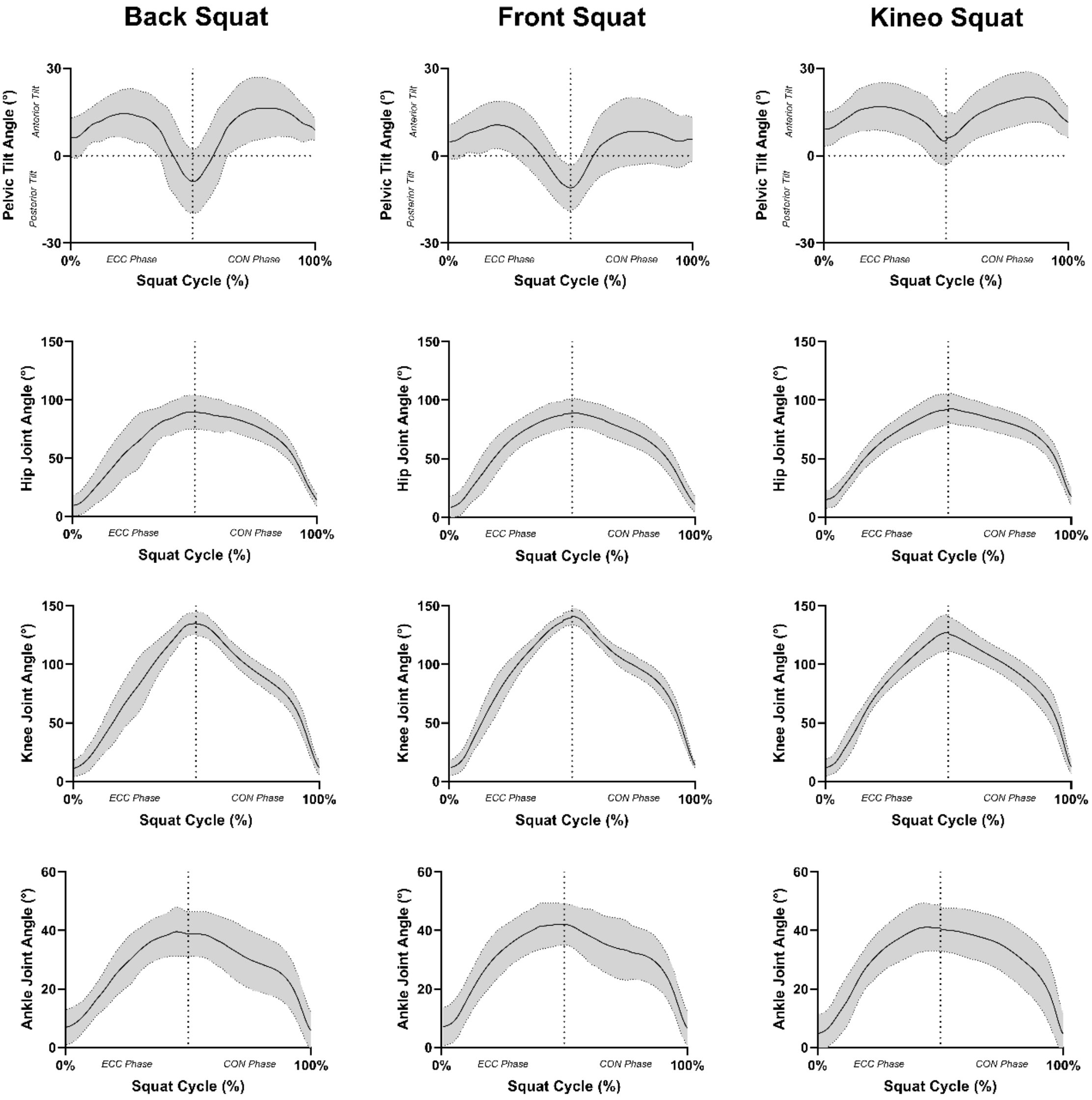

Figure 3-6 Mean ± SD joint angle (°) during the eccentric and concentric phase of the barbell back squat, barbell front squat, and Kineo squat with an external load of 100% of body mass (n = 12). Positive pelvic tilt angle is representative of anterior pelvic tilt, with a negative angle being representative of posterior pelvic tilt. Positive ankle angle is representative of dorsiflexion, with a negative angle being representative of plantar flexion.

There was no effect of squatting variation on the hip joint velocity (F = 0.712, $P = 0.508$) (Figure 3-7). However, there was a large main effect of squatting variation on knee joint velocity (F = 12.121, $P < 0.001$, $\omega^2 = 0.23$) (Figure 3-8), with the Kineo squat displaying significantly greater knee joint velocity than the barbell back squat ($P = 0.008$) and barbell front squat ($P = 0.005$), with no difference found between the barbell back squat and barbell front squat ($P = 0.701$). However, post-hoc analysis identified that the difference in knee joint velocity between variations only occurred under the 50% of body mass loading condition (back squat 263 ± 38 °·s^{-1}, front squat 265 ± 15 °·s^{-1}, Kineo squat 215 ± 19 °·s^{-1}) no significant differences were found between the 3 squat variations at the higher loads ($P > 0.05$).

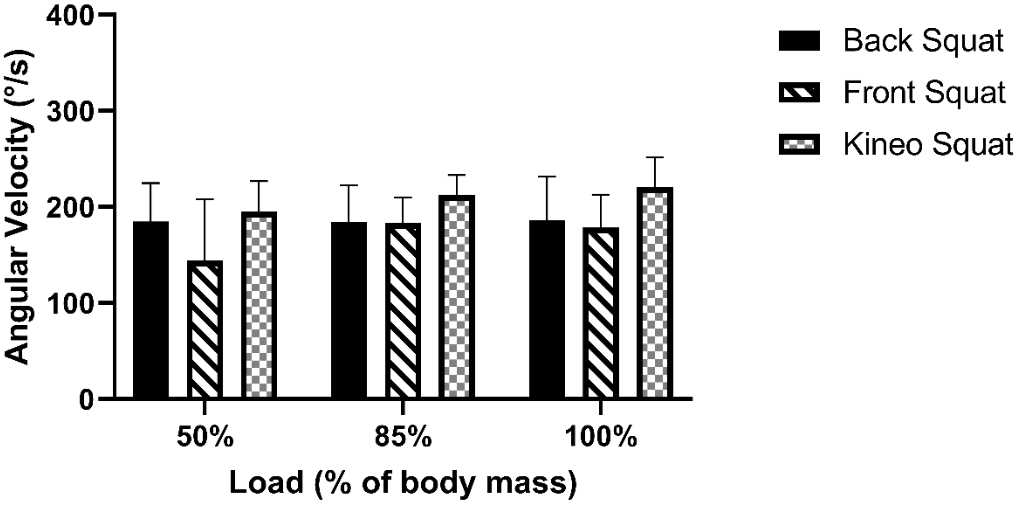

Figure 3-7 Mean ± SD peak hip angular velocity during the barbell back squat, barbell front squat, and Kineo squat during squatting with 50%, 85%, and 100% of body mass (n = 12)

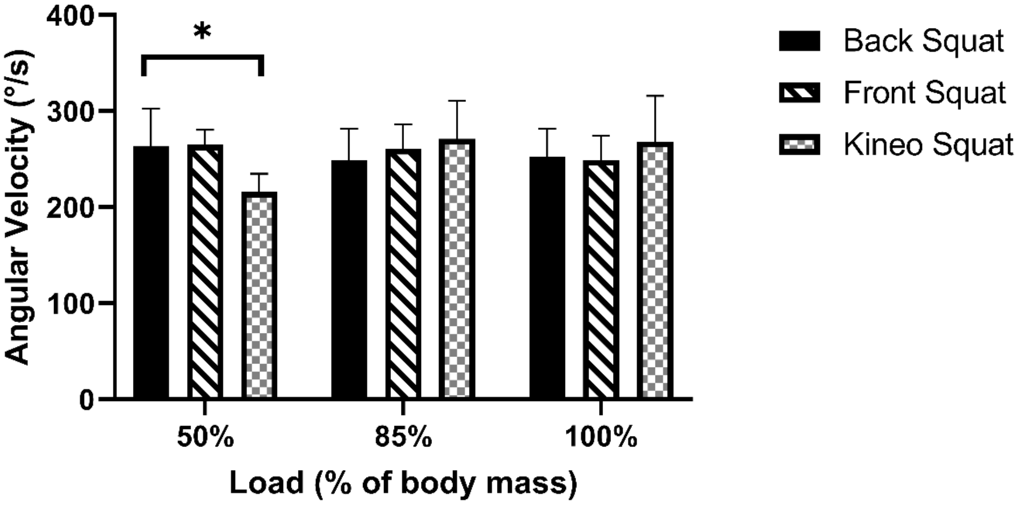

*Figure 3-8 Mean ± SD peak knee angular velocity during the barbell back squat, barbell front squat, and Kineo squat during squatting with 50%, 85%, and 100% of body mass. * Indicates significant difference (P < 0.05) (n = 12).*

There was no effect of squat variation on gluteus maximus activity (F = 1.79, $P = 0.203$) (Figure 3-9). However, there was a medium effect of squat variation on vastus lateralis activity (F = 4.445, $P = 0.032$, $\omega^2 = 0.08$) (Figure 3-10) with the barbell front squat ($P = 0.035$) and Kineo squat ($P = 0.022$) having a significantly greater activity than the barbell back squat during the 50% and 100% trials. There was a large effect of loading on both the gluteus maximus (F = 40.271, $P < 0.001$, $\omega^2 = 0.53$) and vastus lateralis activity (F = 24.69, $P < 0.001$, $\omega^2 = 0.49$). Muscle activity increased as external load increased.

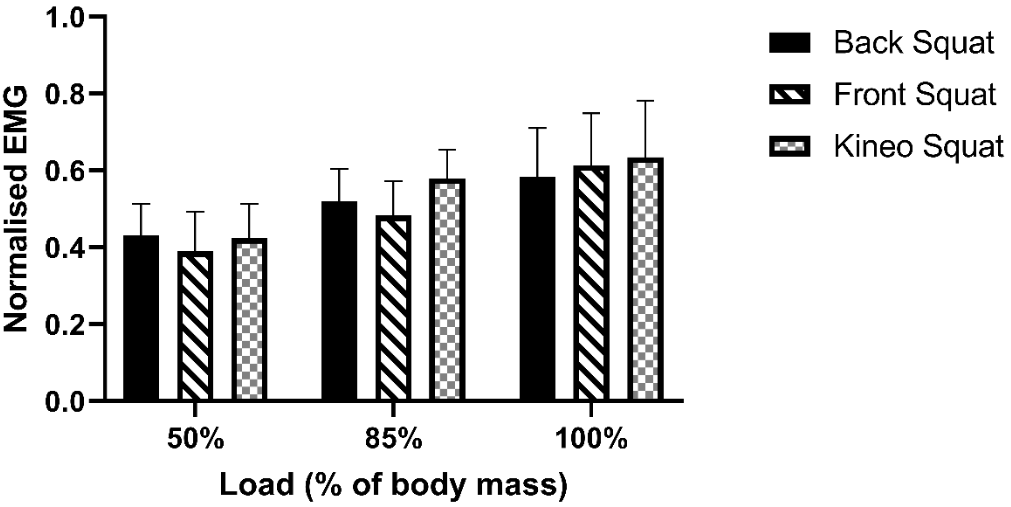

Figure 3-9 Mean ± SD Gluteus maximus normalised EMG during the barbell back squat, barbell front squat, and Kineo squat during squatting with 50%, 85%, and 100% of body mass (n = 12).

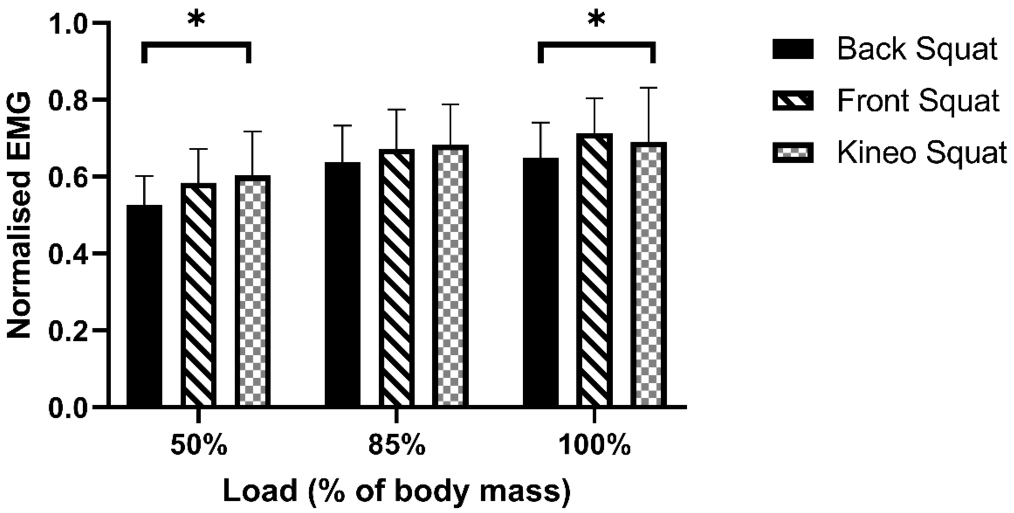

*Figure 3-10 Mean ± SD Vastus lateralis normalised EMG during the barbell back squat, barbell front squat, and Kineo squat during squatting with 50%, 85%, and 100% of body mass. * Indicates significant difference (P < 0.05) (n = 12).*

During the concentric phase of the squat, the peak vastus lateralis activity occurred at a significantly greater knee flexion angle for the barbell back squat (119 ± 13°) and barbell front squat (121 ± 11°) than the Kineo squat (105 ± 17°) (F = 11.286, *P* <0.001, $\omega^2 = 0.06$). There was no effect of squat variation of the hip joint angle at which peak gluteus maximus activity occurred (51 ± 5°) (F = 3.622, *P* = 0.092). There was also no effect of loading on the joint angle at which the peak vastus lateralis activity (F = 0.08, *P* = 0.923) or gluteus maximus activity occurred (F = 0.281, *P* = 0.759).

Analyses of intra-trial reliability revealed coefficients of variations for the hip, knee, ankle, and pelvis ranges of motion to be 2%, 1.5%, 1.3%, and 10.6%, respectively. CV for hip and knee peak joint velocities were 7.8% and 6.7%, respectively and for gluteus maximus and vastus lateralis EMG 17.3% and 6.6%, respectively. Finally, the CV for the hip and knee joint angles at which peak EMG activity occurred for the gluteus maximus and vastus lateralis to be 10.8% and 7.3%, respectively.

3.2 Discussion

The objectives of these exploratory studies were threefold, firstly to assess the validity and reliability of the isovelocity mode of the Kineo. Secondly, to assess the loads and velocities capable of being lifted with the Kineo during and squat, and how these compared to barbell back squatting. Finally, the third objective was to compare the kinematics and muscle activity of the lower limbs during the Kineo squat compared to barbell back squats and barbell front squats.

In regards to reliability and validity of the isovelocity function of the Kineo during concentric and eccentric squatting. The data suggest that the Kineo has a small bias, producing velocities up to ~0.02 m·s^{-1} greater than prescribed. However, this is consistent across all velocities tested (-0.75 to 0.75 m·s^{-1}), and is considered excellent agreement between the measured and prescribed velocities (Haghayegh et al., 2020). These values are similar to those achieved with isokinetic dynamometers (Drouin et al., 2004) which are considered the criterion standard to assess the moment-velocity relationships in single joint movements. Secondly, there is little variation within the prescribed velocities, with repetition variation being ~0.01 m·s^{-1}, and thus the Kineo can be considered highly reliable. Taken together, these results suggest that the Kineo is fit for purpose in delivering a consistent isovelocity function, that is within acceptable limits of the prescribed velocity.

The findings of this study suggest that a greater squat 1RM (~9%) is achievable when using a barbell back squat compared to the Kineo squat. This could be due to the positioning of the external load, with the Kineo squat being loaded anteriorly, thus increasing the moment arm about the knee. Therefore, the knee extensors may play a limiting role in the load lifted during a squat, particularly as the greatest knee joint moment occurs during the initiation of the concentric phase (Choe et al., 2021). This is supported by the observation that the muscle activity of the vastus lateralis (Figure 3-10) is greater during the Kineo squat than during the barbell back squat at equivalent loads.

However, when comparing relative loads such as those that are typically used in resistance training prescription (e.g.,80% 1RM) (Ratamess et al., 2009), the movement velocity between the barbell back squat and Kineo squat at 80% 1RM appears to be similar. These results are similar to those reported by Spitz *et al.,* (2019) who found that the barbell back squat 1RM was ~21% greater than a barbell front squat 1RM, but that mean velocity was similar between squat variations at higher loads. These findings may therefore suggest that the loads lifted and subsequent velocity produced during Kineo squats are comparable to those seen during barbell front squats.

Examining the joint kinematics during the three squatting variations suggest that no differences in hip, knee, and ankle joint ranges of motion exist between squat variations in strength-trained individuals, and that external load up to 100% body mass has no influence on these ranges of motion. However, there is greater vastus lateralis muscle activity in squat variations that are loaded anteriorly (i.e., barbell front squat and Kineo squat) than in posteriorly loaded variations (i.e., barbell back squat). Regardless of variation, no differences were found in gluteus maximus muscle activity.

Within the literature, there is some contrasting evidence to support whether loading position influences squatting kinematics. The presented data supports the findings of Yavuz *et al.,* (2015) suggesting that there are no differences in ranges of motion between the barbell back squat and barbell front squat. The inclusion of the Kineo squat in the present study further confirms that regardless of squat variation, the hip, knee, and ankle ranges of motion appear to remain consistent, providing that the participants have had previous adequate S&C coaching experience. This study also highlights that strength-trained individuals are able to maintain joint ranges of motion regardless of external loading conditions.

As with the kinematic analyses of squatting variation, there are also contrasting findings within the literature regarding the differences between muscle activity. Gullett *et al.,* (2009) found no differences in terms of muscle activity between squat variations. However, the data in the present study and Yavuz *et al.,* (2015) found greater quadricep activity (~6%) during the barbell front squat than the barbell back squat, with no differences for the gluteus maximus. Data for the Kineo squat was similar to the barbell front squat in terms of muscle activity, with normalised EMG values being ~70% and ~60% for the vastus lateralis and gluteus maximus, respectively, both of which were significantly greater than during the barbell back squat. For all squat variations, the vastus lateralis activity was greatest during the start of the concentric phase, whilst gluteus maximus activity was greatest later in the concentric phase which is consistent with what is reported within the literature (Robertson et al., 2008).

Considering the presented data, it appears that squats performed on the Kineo have similar kinematics to those of both front and back barbell squats. However, greater vastus lateralis muscle activity was found during barbell front squat and the Kineo squat than the barbell back squat, and greater loads were capable of being lifted in the barbell back squat than the Kineo squat. Therefore, the squats performed on the Kineo can be regarded as an acceptable squat variant, being more similar to the barbell front squat than the barbell back squat. The data obtained from future studies can be considered applicable to the wider squatting based research.

3.3 Conclusion

This chapter aimed to assess whether the Kineo training System was suitable for the purposes of this PhD thesis. This began by comparing; the loads lifted, the kinematics, and the muscle activity of the lower limbs, during squats performed with a barbell to those when performing squats on the Kineo. The results indicate that squats performed on the Kineo are similar to those performed with a barbell. Analysis of lower limb joint ranges of motion suggest that regardless of the squat variation employed, ranges of motion will remain consistent between variations. Therefore, data obtained from squats performed on the Kineo appear to be ecologically valid and be transferable to applied practice.

The second aim of this chapter was to assess whether the isovelocity mode on the Kineo was valid and reliable enough to utilise as a research instrument. This was assessed by comparing the prescribed velocity against a direct measure of the velocity via 3D motion capture cameras. The findings from this indicate that there is a small, but insignificant variation between the velocities produced during each trial, and that there is a small systematic bias for the Kineo to operate at velocities up to ~0.02 $m \cdot s^{-1}$ greater than prescribed. However, as this bias is consistent across all concentric and eccentric velocities, this can be accounted for during future experimental investigations.

Taken together, it appears that the Kineo is fit for the purpose of examining the aims of this PhD thesis in order to facilitate squatting that is similar in mechanics to barbell squatting, and to facilitate isovelocity loading in order to assess the multi-joint force-velocity relationship. This is confirmed by the kinematics, muscle activity and loading of the Kineo squat being comparable to those seen during conventional squatting modalities, and the Kineo isovelocity mode being valid and reliable.

Chapter 4.

Determining Concentric and Eccentric Force Velocity Profiles During Squatting

4.1 Abstract

Introduction The force-velocity relationship of muscular contraction has been extensively studied. However, previous research has focused either on isolated muscle or single-joint movements, whereas human movement consists of multi-joint movements (e.g. squatting). Therefore, the purpose of this study was to investigate the force-velocity relationship of isovelocity squatting.

Methods 15 male participants (24 ± 2 years, 79.8 ± 9.1 kg, 177.5 ± 6 cm) performed isovelocity squats on a novel motorised isovelocity device (Kineo Training System) at three concentric (0.25, 0.5, & 0.75 m.sec^{-1}) and three eccentric velocities (-0.25, -0.5, & -0.75 m.sec^{-1}). Peak vertical ground reaction forces, that occurred during the isovelocity phase, were collected using dual force plates (2000Hz) (Kistler, Switzerland).

Results The group mean squat force-velocity profile conformed to the typical *in-vivo* profile, with peak vertical ground reaction forces during eccentric squatting being 9.5 ± 19 % greater than isometric ($P = 0.037$), and occurring between -0.5 & -0.75 m.sec^{-1}. However, large inter-participant variability was identified (0.84-1.62x isometric force), with some participants being unable to produce eccentric forces greater than isometric. Sub-group analyses could not identify differences between individuals who could/could not produce eccentric forces above isometric, although those who could not tended to be taller.

Conclusions These finding suggest that variability exists between participants in the ability to generate maximum eccentric forces during squatting, and the magnitude of eccentric increase above isometric cannot be predicted solely based on a concentric assessment. Therefore, an assessment of eccentric capabilities may be required prior to prescribing eccentric-specific resistance training.

4.2 Introduction

The force-velocity relationship defines an important dynamic property of muscle contraction (Alcazar et al., 2019, Fenn and Marsh, 1935, Hill, 1938). As discussed in chapter two, in isolated muscles, eccentric forces during lengthening of an active muscle are known to be up to 80% greater than isometric forces (Edman, 1988). However, *in-vivo*, where muscle forces are applied and measured as joint moments, the moment-velocity relationships display smaller and more variable differences between eccentric and isometric joint moments. The magnitude of this difference depends on the joints involved; for elbow flexion/extension 12-25% (Chapman et al., 2005, Hortobágyi and Katch, 1990, Komi, 1973), for ankle dorsi/plantar-flexion 12-18% (Connelly and Vandervoort, 2000, Liederbach and Hiebert, 1997), for knee extension 0-22% (Dudley et al., 1990, Melo et al., 2016, Pain and Forrester, 2009), and for hip extension 8-11% (Boling et al., 2009).

The reduced eccentric enhancement of joint moments *in-vivo* is thought to be due to a unique eccentric neural activity strategy (Enoka, 1996) that decreases; voluntary activation (~15%) (Babault et al., 2001, Beltman et al., 2004), motor unit firing rate (~35%) (Del Valle and Thomas, 2005), and alters cortical and spinal excitability (Duclay et al., 2011, Duclay et al., 2014), when compared to isometric contractions. It is theorised that if it were not for these neural factors, the eccentric joint moment would be ~60% greater than typically observed during in-vivo single joint movements (Pain and Forrester, 2009). Due to these neural constraints and the variability of their effects, force-velocity relationships must be established *in-vivo* so that the complexity of co-ordinating human movement may be considered, rather than relying on *ex-vivo* measurements, before eccentric loading recommendations for applied training can be made.

Our current understanding of the eccentric portion of the force/moment-velocity relationship *in-vivo* has primarily been derived from single-joint movements, e.g., hip extension (Boling et al., 2009), knee extension (Dudley et al., 1990, Melo et al., 2016, Pain and Forrester, 2009), plantar flexion (Connelly and Vandervoort, 2000, Liederbach and Hiebert, 1997). Although single-joint models account for the neural constraints of voluntary contractions and are experimentally appealing as they allow tighter control of movement variables (e.g., joint/muscle/fibre velocity, angle/muscle length, and range of movement), human movement is not isolated into single-joints, but is rather a combination of multi-joint movement patterns. Due to the increased complexity of multi-joint movements and subsequent differing neural activation strategies (Behm et al., 2003) compared to single joint movements, multi-joint force-velocity relationships may differ from single joint force-velocity relationships.

As discussed in chapter two, section 2.3.2, studies have demonstrated that the concentric portion of multi-joint force-velocity relationships (e.g., the rising phase of a loaded squat) are typically quasilinear (Bobbert, 2012, Rahmani et al., 2001, Zivkovic et al., 2017). This is in contrast to single-joint moment-velocity relationships, which are described as curvilinear (de Brito Fontana et al., 2014, Hauraix et al., 2017, Pain and Forrester, 2009).

Studies on the multi-joint force-velocity relationship have been performed utilising both traditional movements (e.g., squatting) (Spudić et al., 2020), and ballistic movements (e.g., sprinting, jumping, push-offs) (Morin and Samozino, 2016, Samozino et al., 2010) as well as during cycling (Rudsits et al., 2018, Driss et al., 2002). This has resulted in practitioners being able to identify performance characteristics for improvement, that can then be targeted with training interventions, based upon the slope of the concentric force-velocity curve compared to a calculated optimal profile (Samozino et al., 2012).

Unfortunately, the majority of the multi-joint force-velocity research has focused on the concentric portion (Spudić et al., 2020), and much less evidence exists regarding the nature of the eccentric portion of the multi-joint force-velocity relationship *in-vivo*, likely due to the difficulty, and inherent risk, of applying supra-maximal external loads during high movement velocities. There is only one study to date which has investigated the eccentric portion of the force-velocity relationship in a lower body multi-joint task (Hahn et al., 2014). Utilising a leg-press model, eccentric GRFs were up to 15% greater than isometric forces. Eccentric force production peaked at a knee flexion velocity of $-60°\cdot s^{-1}$ and decreased as eccentric velocity increased to $-180°\cdot s^{-1}$ (Hahn et al., 2014). This suggests that the eccentric portion of multi-joint force-velocity relationship is similar in shape to the single joint force-velocity relationship, . However, the leg-press, as used by Hahn et al. (2014), does not allow for full hip extension, and is not as effective at improving athletic performance qualities as the squat (Wirth et al., 2016). Although previous studies have examined the force characteristics of the eccentric phase of the squat, and were discussed in chapter two (McNeill et al., 2021, Frohm et al., 2007), no previous study has investigated the eccentric portion of the force-velocity relationship in the squat.

There are several reasons why it is difficult studying the force-velocity profile of squatting. Firstly, it is complicated given the muscular effort required to control the speed of descent (i.e., the eccentric phase) of any given load increases throughout the eccentric range of motion as the hips and knees flex (Bryanton et al., 2012). In layman terms, although an individual may be able to withstand a supra-maximal load at the start of a squat, there is an increased likelihood of failure, concomitant with risk of injury, during the approach to a deeper squat position. Furthermore, movement velocity varies over the duration of the movement (Miletello et al., 2009), so accurately measuring eccentric force and velocity over repeated trials may prove challenging.

In order to overcome these difficulties, advances in technology, using the Kineo Training System (Figure 4-1), allow for the application of multi-joint isovelocity movements, by manipulating the external force at a constant velocity over the duration of the exercise. This would therefore allow concentric and eccentric isovelocity squatting to occur in a safe, controlled manner whilst collecting GRFs, thus overcoming the limitations of previous eccentric loading approaches (For a detailed discussion on the Kineo refer to chapter three).

Absolute force production is regulated by both the mechanical properties of the muscle and the activation of the muscle (Fitts et al., 1991). Therefore, it would be expected that the absolute concentric and eccentric forces an individual can produce would be correlated. However, it has been shown that the magnitude of eccentric force an individual can produce above isometric (i.e. normalised force) cannot be predicted from their concentric performance (Harden et al., 2019).

Therefore, the primary aim of this study was to establish the force-velocity relationship during isovelocity squatting. This knowledge will allow the development of evidence-based training recommendations for future eccentric overload interventions (which we be performed in chapter six). In current practice, accentuated-eccentric training loads are typically up to 20% greater than the concentric 1RM (Harden et al., 2020a). However, this relies on the assumption that this overload is suitable for all individuals which may not be correct as the maximum eccentric strength of individuals may vary. Therefore, a secondary aim of this study was to identify whether concentric strength influences the magnitude of the eccentric force increases above the isometric level. It was hypothesised that (1) eccentric squatting forces would be greater than isometric and concentric forces; and (2) absolute eccentric forces would be correlated with absolute concentric forces, however normalised eccentric forces would not be correlated with absolute concentric force.

4.3 Methods

Participants: Fifteen strength-trained males (age; 24 ± 2 years, body mass; 79.8 ± 9.1 kg, height; 177.5 ± 6 cm, training age; 3.5 ± 1.5 years) volunteered for this study. All participants could demonstrate a good squatting technique, as determined by a qualified S&C coach, and frequently (>1 times per week) performed the squat within their habitual resistance training practice. Strength-trained participants were selected for this study in order to limit the known negative effects of the eccentric neural activation strategy in untrained participants (Aagaard, 2018). Prior to participation, written informed consent was completed and this study received ethical approval from Liverpool John Moores University research ethics committee (19/SPS/038).

Experimental Protocol: Participants reported to the Liverpool John Moores laboratories on three occasions. The first and second visits were used for participant familiarisation with the experimental protocols, and to measure body mass (to the nearest 0.1 kg, on electronic scales; SECA, Germany), and height (to the nearest 0.5 cm, with a stadiometer; SECA, Germany). Participants completed a standardised warmup following the RAMP protocol (Jeffreys, 2006) (for more details on this warmup, please refer to the appendices section), which was concluded with several progressively heavier sets of loaded squats on the Kineo Training System on which all experimental trials were also completed. Following the warmup, participants underwent a familiarisation session inclusive of concentric and eccentric isovelocity squatting. Squat stance was standardised with feet shoulder-width apart and externally rotated ~20°. Squatting range of motion was determined, whereby the eccentric phase started with the participant standing with hips and knees fully extended and lasted until the participant had squatted down to a depth where the top of the thigh was parallel to the ground. The concentric phase began after the eccentric phase finished and until the participant had fully extended the hips and knees (Figure 4-1). Squatting depth was confirmed by analysis of cable displacement during experimental trials.

Figure 4-1 Kineo Training System; participant is connected to an electric motor via a hip/shoulder harness attached to a cable pulley system. A – The start of the eccentric phase/end of concentric phase, B – The end of the eccentric phase/start of the concentric phase. Two additional force plates, one under each foot, were added to this experimental set up (not shown) to measure vertical ground reaction forces (N).

Experimental data were collected during the third visit, 4-10 days following the final familiarisation session. Participants refrained from strenuous physical activity for 48 hours prior to testing and were asked to arrive in a fed and hydrated state. Following the standardised warmup, participants completed a total of six maximum effort isovelocity trials at 0.75, 0.5, 0.25, -0.25, -0.5, and -0.75 m.sec^{-1}, whereby positive and negative values were indicative of concentric and eccentric directions, respectively, with three repetitions per trial.

During concentric trials, participants began by standing with the hips and knees extended, performed a submaximal (~80% perceived effort) eccentric isovelocity squat at -0.25 m.sec^{-1}, immediately followed by a maximum effort isovelocity concentric squat at the prescribed trial velocity (Figure 4-2). Participants were provided visual feedback to ensure they produced an effort of 80% during the submaximal eccentric phase, with this value having been identified during the second familiarisation session.

During eccentric trials, participants began by standing with the hips and knees extended, performed a submaximal eccentric isovelocity squat (~80% perceived effort, -0.25 $m.sec^{-1}$), followed by a near-maximal concentric isovelocity squat (~90% perceived effort, 0.25 $m.sec^{-1}$), before performing the maximal effort isovelocity eccentric squat for which data were recorded (Figure 4-3). Visual feedback was provided as per the concentric trials. The near maximal concentric effort immediately prior to the maximal eccentric effort ensured preload on the musculature, which is required for maximal eccentric efforts (Hahn, 2018, Linnamo et al., 2006). During the maximal eccentric trial, the participant maximally resisted the downwards displacement of the external cable at the respective velocity until the end of the range of motion. Three repetitions were completed at each velocity, with five minutes passive rest between each trial.

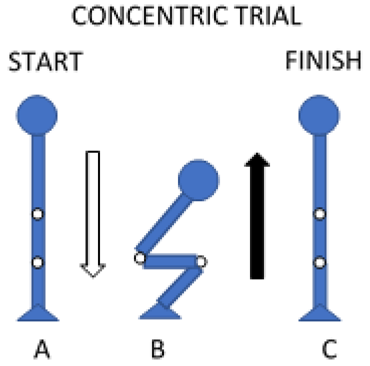

Figure 4-2 Schematic of concentric isovelocity squatting trials. A) Start position, B) Submaximal eccentric squat to parallel squat depth, C) Maximal effort concentric squat. Arrows represents direction of movement; solid black arrow denotes maximum effort trial that was recorded for data analysis.

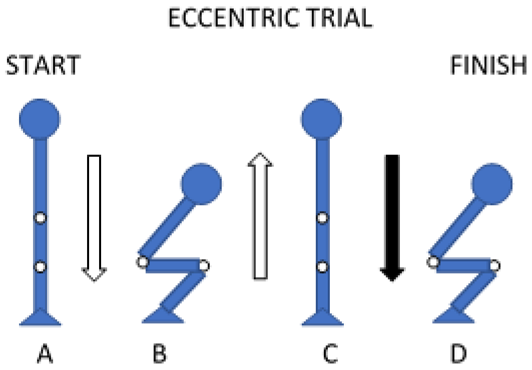

Figure 4-3 Schematic of eccentric isovelocity squatting trials. A) Start position, B) Submaximal eccentric squat to parallel squat depth, C) Near maximal concentric squat to full hip/knee extension to preload, D) Maximal effort eccentric squat. Arrows represents direction of movement; solid black arrow denotes maximum effort trial that was recorded for data analysis.

Data Acquisition and Analyses: During all trials, GRFs (N) under each foot were collected via a dual force plate system (9287c, Kistler, Switzerland), sampling at 2000 Hz. Analogue signals were amplified and converted to a digital signal prior to being collected in Qualisys Track Manager (Qualisys, Sweden) and then exported to Visual 3D (C-Motion, USA) for subsequent analysis. The greatest peak vertical GRFs from each of the six experimental conditions (Concentric; 0.75, 0.5, & 0.25 $m.sec^{-1}$, Eccentric; -0.25, -0.5, & -0.75 $m.sec^{-1}$) were used for analysis. GRFs were then processed via a 4th order Butterworth filter with a cut-off frequency of 6 Hz, then the forces of the dominant and non-dominant limb were summed together.

During these trials, only forces that occurred during the isovelocity phase of the squat were used, which were defined from the measured movement velocity profile. To confirm actual squat velocity for each defined trial, reflective markers were placed on the cables that attached the participant to the Kineo Training System, and were monitored by three 3D motion capture cameras (Opus 3 series, Qualisys, Sweden), sampling at 200 Hz.

Forces were plotted against the target velocity to create force-velocity relationships for each participant and were normalised against a predicted isometric force. A joint-angle specific maximum isometric force could not be measured as peak forces occur at different joint angles during the concentric and eccentric phase (Melo et al., 2016), and these can differ between participants. Instead, isometric force was calculated for zero velocity from a cubic polynomial regression equation fitted to each participant's measured force-velocity profile. Calculating isometric force in this manner has been previously used (Morin and Samozino, 2016, Samozino et al., 2010) and shown to be robust.

Statistical Analyses: All data were statistically analysed using SPSS (version 27, IBM, USA). All data were checked for normality, and homogeneity of variance using a Shapiro-Wilk and Levene's tests, respectively. A one-way repeated measures ANOVA with six factor levels was used to test for differences in the peak force from each velocity. As there was a violation of sphericity ($P < 0.001$), a Greenhouse-Geisser correction was used (Atkinson, 2001). A two-way repeated measures ANOVA (2x6) was used to test for differences between the dominant and non-dominant limbs. Finally, a one-way repeated measures ANOVA was used to tests for differences in the squat depth (%) at which peak force occurred (whereby 0% is the position at which the hips & knees are fully extended, and 100% is the position at which the thighs were parallel to the ground). Statistical significance was assessed by an alpha level of 0.05. Statistically significant results underwent a Holm-Bonferroni post-hoc analysis. All data are presented as mean ± SD, unless otherwise stated. Correlation analysis was performed to determine if maximal concentric strength influenced eccentric force production. Absolute and normalised peak force from all eccentric trials (-0.25, -0.5, & -0.75 m.sec^{-1}) were correlated against the trial in which the greatest concentric force was produced (0.25 m.sec^{-1}).

Coefficients of variation and intraclass correlation coefficients were also performed to identify the reliability of GRFs between repetitions at each velocity. Intraclass correlation coefficient was interpreted in line with recent guidelines (Koo and Li, 2016).

4.4 Results

The group mean force during isovelocity squatting (3166 ± 695 N) which was recorded during the highest velocity eccentric trial (-0.75 m.sec^{-1}) (Figure 4-4) conformed to the expected *in-vivo* force-velocity profile, with the maximum force being 1.095 ± 0.19 times greater than isometric. There was a significant main effect of squat velocity on vertical GRF ($F_{1.85, 25.87}$ = 22.059, $P < 0.001$).

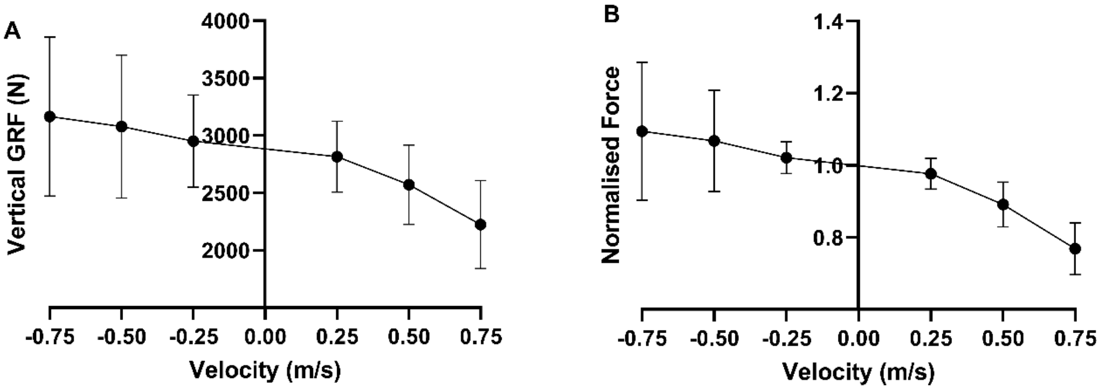

Figure 4-4 Group mean ± SD Force-Velocity relationships of isovelocity squatting. A) Vertical ground reaction force (N). B) Normalised force relative to isometric. Concentric velocities are +ve, eccentric velocities are -ve. (n = 15)

Post-hoc analysis identified that the eccentric -0.75 m.sec^{-1} velocity trial (3166 ± 695 N) (*P* = 0.037, 95% CI of Δ = 24 to 657 N) and the -0.5 m.sec^{-1} velocity trial (3080 ± 623 N) (*P* = 0.037, 95% CI of Δ = 18 to 509 N) both produced greater mean peak forces than the highest recorded concentric velocity trial (0.25 m.sec^{-1}, 2816 ± 308 N). However, the difference in the peak force between the eccentric -0.25 m.sec^{-1} (2952 ± 402 N) and concentric 0.25 m.sec^{-1} trials did not reach significance (*P* = 0.288, 95% CI of Δ = -14 to 287 N). Neither was the difference between the eccentric -0.75 and -0.5 m.sec^{-1} trials statistically different (*P* = 0.300, 95% CI of Δ = -86 to 258 N). Peak forces for all trials occurred at 36-41% (±6-14%) of squat depth regardless of squat direction and velocity (F_5 =0.846, $P = 0.521$).

There was an asymmetry in the forces produced between the dominant and non-dominant limbs ($F_{15} = 10.002$, $P = 0.007$), with the smallest limb asymmetries identified during the higher velocities (~3%), and largest asymmetries occurring during the slow velocities (~6%). However, there was not a significant interaction of the dominant vs non-dominant limb on the magnitude of forces produced at each velocity ($F_5 = 0.522$, $P = 0.759$), and thus this did not influence the shape of the force-velocity relationship.

4.4.1 Individual Responses

There was inter-participant variability between the eccentric forces produced. Analyses of individual data revealed that some participants did not produce eccentric forces greater than isometric (Figure 4-5). Table 4-1 summarises the characteristic differences between those individuals who had no eccentric-increase (normalised eccentric force ≤ 1.0 across all trials) and those who had an eccentric-increase (>1.0). No significant differences were found between groups ($P = 0.059\text{-}0.971$), although the no eccentric-increase group tended to be taller and heavier.

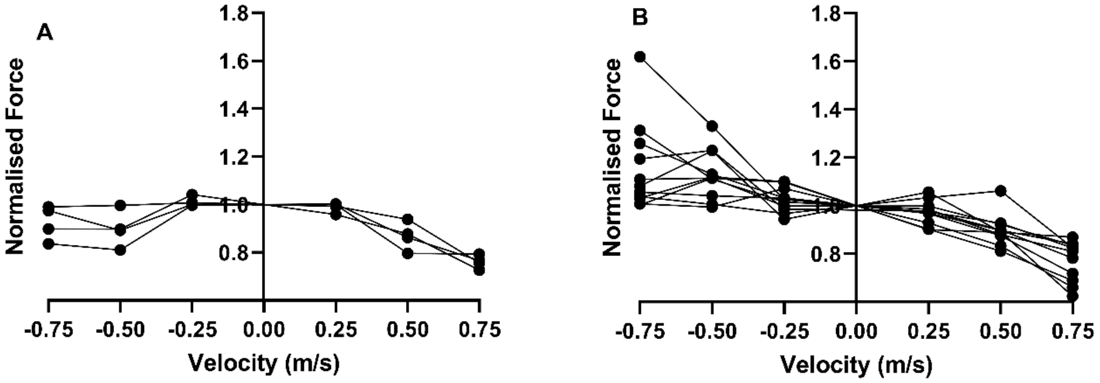

Figure 4-5 Force-Velocity relationship from isovelocity squatting in A) Sub-group of participants that did not achieve an eccentric force increase (normalised eccentric force ≤ 1.0) (n=4) and B) Sub-group of participants that did achieve an eccentric force increase group (normalised eccentric force > 1.0) (n=11).

Table 4-1 Individual and Means ± SD for characteristics of participants who did not achieve an eccentric-increase in force (n =4) and those who did (n=11). Data are in ascending rank order for normalised maximum eccentric force.

	Participant	Normalised Eccentric force (-0.75 m.sec^{-1})	Body mass (kg)	Height (cm)	Age (years)	Barbell Squat 1RM (kg)	Training Age (years)	Squat 1RM/BM
No Eccentric-Increase	k6	0.84	85.65	193.5	26	120	3	1.40
	k5	0.90	83.6	179.5	22	150	2	1.79
	k4	0.97	82.85	182	25	120	3	1.45
	k9	0.99	94	173	25	200	7	2.13
Mean ± SD		0.93 ± 0.07	86.5 ± 5	182 ± 8.5	25 ± 2	147.5 ± 37.5	4 ± 2	1.69 ± 0.33
Eccentric-Increase	k12	1.00	80.7	182	24	127.5	4	1.58
	k2	1.01	69	178.5	23	105	5	1.52
	k3	1.03	68.6	171	20	125	3	1.82
	k8	1.04	63	172	24	92.5	1	1.47
	k11	1.06	81.3	178.5	23	150	4	1.85
	k10	1.08	87.4	175	23	140	5	1.60
	k1	1.11	65.5	174	24	115	4	1.76
	k7	1.19	88.3	178.5	27	140	2	1.59
	k14	1.26	82.7	172	21	132.5	4	1.60
	k15	1.31	84.1	181.5	27	140	4	1.66
	k13	1.62	81	171	26	120	2	1.48
Mean ± SD		1.16 ± 0.18	77 ± 9.5	175 ± 4	24 ± 2	126 ± 18	3 ± 2	1.63 ± 0.13

Additionally, there was a modest to high positive correlation between absolute peak concentric force (0.25 m.sec^{-1}) and absolute peak eccentric force (-0.75 m.sec^{-1}; r_{15} = 0.544, 95% CI of Δ = 0.04 to 0.83, P = 0.036, -0.5 m.sec^{-1}; r_{15} = 0.745, 95% CI of Δ = 0.38 to 0.91, P = 0.001, -0.25 m.sec^{-1}; r_{15} = 0.738, 95% CI of Δ = 0.36 to 0.91, P = 0.002) (Figure 4-6). However, there was no significant correlation between absolute peak concentric force (0.25 m.sec^{-1}) and the isometric-normalised eccentric force (-0.75 m.sec^{-1}; P = 0.757, -0.5 m.sec^{-1}; P = 0.19, -0.25 m.sec^{-1}; P = 0.628) (Figure 4-6).

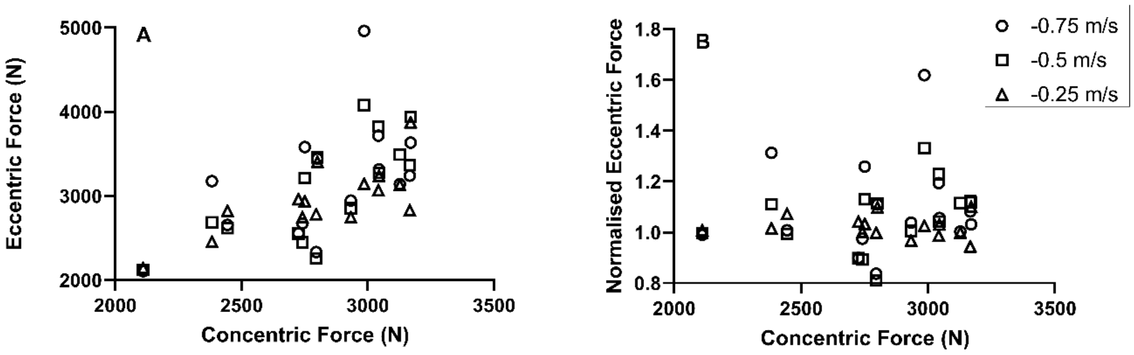

Figure 4-6 Scatter plots showing A) positive linear correlation between concentric force and eccentric force at -0.75 (P = 0.036), -0.5 (P = 0.001), & -0.25 m.sec-1 (P = 0.002). B) No correlation between concentric force and normalised eccentric force (P = 0.19 to 0.757) (n = 15).

Analysis of repetition-to-repetition variation of vertical ground reaction forces within each velocity identified acceptable coefficients of variation (6.1 – 9.2%) and intraclass correlation coefficients (0.84 – 0.93) (McMaster et al., 2014). These values are similar to those reported for both traditional (Fairus et al., 2016), and isometric squats (Palmer et al., 2018a).

4.5 Discussion

The main findings of this study establish that maximal isovelocity squatting conforms to the well-established pattern of the force-velocity relationship, with peak eccentric forces being ~10% greater than isometric forces. However, inter-participant variability existed at higher eccentric velocities. Although most participants conformed to the expected force-velocity profile, some individuals did not produce eccentric forces greater than isometric, whilst one produced an extremely high eccentric force (Table 4-1, participant K13).

The first hypothesis is accepted, since the group mean eccentric force peak was ~10% greater than isometric (Figure 4-4), which was similar to the results reported by (Hahn et al., 2014). These values are both far below isolated muscle forces, which can reach up to 80% greater than isometric (Edman, 1988). These differences might be explained by the previous discussed eccentric neural activation strategies plus altered activity levels occurring during multi-joint movements (Behm et al., 2003), which may impair the ability to produce maximal force (Maffiuletti et al., 2016). Additionally, the greater the degrees of freedom within a movement, the more unstable a joint becomes (Wuebbenhorst and Zschorlich, 2011), requiring the musculature to stabilise the movement rather than produce maximal force (Kornecki and Zschorlich, 1994, Wuebbenhorst and Zschorlich, 2012). These two neural mechanisms could cause a general decrease in force production, which is consistent with previous literature (Bryanton et al., 2012) showing that during concentric squatting, the lower body musculature can only produce 60-80% of its predicted maximum force compared to when tested in a single-joint isometric state. Rapid increases in neural activity levels have been shown during eccentric-specific resistance training (i.e., modulation of the load/velocity of the eccentric phase of an exercise) (Seynnes et al., 2007), therefore it may be hypothesised that rapid improvements in eccentric squatting strength may be achieved by overcoming the neural limitations of eccentric squatting following a short-term training intervention.

Additionally, unlike single-joint movements where kinematics are constrained, the kinematics of squatting can differ between the concentric and eccentric phase (Swinton et al., 2012), which may prevent the hip and knee joints simultaneously being at their optimal angle to produce maximal joint moments, despite squat depth remaining constant. The combined contribution of the two joints to the GRF could therefore be reduced (Beckham et al., 2018), in particular during the eccentric trials compared to the concentric trials, limiting the eccentric squatting force. Future studies should utilise inverse dynamics to study the individual joint contributions to eccentric squatting, and assess squatting kinematics, rather than just squat depth, to better understand the mechanisms contributing to the strength capacity during eccentric squatting and inform targeted training prescription guidance.

The force-velocity relationship of squatting followed the same sigmoidal shape that exists in single joint actions and isolated muscle (Alcazar et al., 2019), reflecting the established mechanics of muscle contraction. The shape of the force-velocity curves produced in this study were also similar between the dominant and non-dominant limbs, with the asymmetries between limbs (<6%) being similar to the asymmetries previously reported in bilateral movements (Simon and Ferris, 2008). However, following the initial increase in eccentric force from -0.25 m.sec^{-1} to -0.5 m.sec^{-1}, there was a plateau between -0.5 m.sec^{-1} and -0.75 m.sec^{-1}. In practical terms, it appears that there exists an optimal velocity range that facilitates the greatest production of eccentric forces, which in turn should produce the greatest physiological response (Rindom et al., 2019). The data suggests that the greatest forces occur between -0.5 to -0.75 m.sec^{-1}. However, due to the individual differences when performing eccentric actions (discussed below), it may be prudent to perform assessments of eccentric capabilities prior to prescribing eccentric resistance training protocols.

4.5.1 Individual Differences

When exploring the data, it becomes evident that a greater variance in the forces produced occurred during the eccentric trials than during the concentric trials (see the standard deviations in Figure 4-4). At -0.75 m.sec^{-1}, the normalised force ranged from 0.84-1.62 around a mean of 1.1, indicating that although many individuals generated the physiologically expected eccentric force above isometric (Figure 4-5B), some did not (Figure 4-5A), even though all participants were familiar with resistance training and the squat movement. This large inter-participant variability was still apparent even when excluding the participant who achieved an eccentric force that was 1.6 times greater than isometric. Variability between individuals in the ability to produce eccentric moments has been reported previously during knee-extension/flexion maximum moment assessments (Hahn, 2018). Group mean knee moments were reported by Hahn *et al.,* (2018) as being 1.2 times isometric, however some individuals were shown to be capable of producing moments 1.8 times isometric (Hahn, 2018). Therefore, the measurement of a maximal eccentric force of 1.6 times the isometric agrees with the limited previous data.

During this study, it was also assessed whether the individual ability to generate eccentric forces was associated with overall squatting ability. Supporting our hypothesis, normalised eccentric force was not correlated with absolute concentric force (Figure 4-6B), and so it was found that strength itself did not determine whether an individual produced eccentric forces greater or less than isometric. This is supported by previous research that has shown that there is difficulty in accurately predict eccentric strength from a concentric strength test (Harden et al., 2019).. Previous training interventions have demonstrated that eccentric-specific resistance training causes an increase in eccentric force production (Seger et al., 1998, Spurway et al., 2000), probably due to movement-specific improvements in muscle activity and a greater lengthening of muscle fascicles (Franchi et al., 2014). Therefore, it would be expected that individuals with a history of eccentric-specific resistance training would display a greater normalised eccentric force. However, although all participants had a history of resistance training (3.5 ± 1.5 years) and could squat a minimum of 1.4 times body weight (Table 4-1), none of these participants had a notable history of eccentric-specific resistance training, so this does not explain the variances found in this study.

There are other factors that may influence eccentric squatting force that this study did not specifically assess, but comparison of the sub-groups (Table 4-1) may offer some insight. Although all participants squatted to a depth where the centre of the hip was below the centre of the knee, squatting technique can vary between individuals (Myer et al., 2014). Although not statistically significant, the group that had no eccentric-increase were taller. Taller individuals may adopt a more hip-dominant squatting technique in order to counter balance (Myer et al., 2014), and this technique can change between the concentric and eccentric phases. This may result in differing hip, knee, and ankle joint ranges of motion, which would influence the amount of force exerted into the ground (Beckham et al., 2018), and thus the profile of the force-velocity relationship. Future research may explore the effects of height and limb lengths on the joint contributions and their effect on exploiting the greater strength capacity of eccentric squatting.

Another factor worth considering is the ability to activate the musculature during eccentric squatting. This could explain the inter-participant variability. Although it was not assessed in this study, the ability to activate skeletal muscle has been shown to correlate with force production (Folland et al., 2014). Eccentric contractions have a unique neurological activation strategy, compared to concentric/isometric contractions (Enoka, 1996) and activation capacity is known to differ between individuals (Avrillon et al., 2021), furthermore eccentric activation can be trained (Aagaard et al., 2000). Therefore, measurements of eccentric activity should be included in future research. However, caution should be taken when interpreting these data as this data only represented the capabilities of the individual on the given day. Future research should perform repeat measures of eccentric force assessment to identify the session variability.

4.5.2 Practical Applications

The presented data suggests that maximal concentric strength does not influence the ability to maximise relative eccentric force production, and therefore practitioners should attempt to measure eccentric capability prior to prescribing eccentric-specific resistance training rather than relying on standardised loads relative to concentric maximums (Harden et al., 2020a). This lack of eccentric-specific assessment, and thus individualisation of training programs, may explain why the efficacy of eccentric-specific resistance training (e.g., accentuated-eccentric loading) has been debated in the past (Douglas et al., 2018).

In many applied settings, eccentric-specific assessment is achieved under external load (Harden et al., 2019), which will dictate movement velocity, rather than the imposition of isovelocity movements. This presents practical challenges if done using traditional weightlifting techniques. In this study, however, the Kineo training system proved effective in delivering the fast eccentric squatting efforts required to identify a plateau in eccentric force, allowing individualised force-velocity profiles to be developed. However, for practitioners that do not have access to this equipment, field-based assessment of eccentric capabilities may need to be developed in order to individualise eccentric-specific resistance training. Future research should also examine the effects of different eccentric protocols on movement velocity, and subsequent force production, and the ability of resistance training interventions to train and improve these aspects of performance.

Although this study focused on establishing underpinning knowledge of the multi-joint force velocity curve, some findings may be extrapolated to applied practice. In applied settings, accentuated-eccentric loading is often coupled with a slower eccentric velocity, which results in an eccentric phase duration of 3-4 seconds (Harden et al., 2020a), equivalent to a velocity slower than -0.25 m.sec^{-1}. However, the data suggests that at this slow eccentric velocity, accentuated-eccentric loading squatting may only provide a 2% benefit in terms of peak forces imposed on the body, when compared to maximal effort traditional squatting. In contrast, the data reported here demonstrate that many trained individuals are able to generate larger forces and experience greater training loads in faster eccentric trials, which may provide an accentuated stimulus for adaptation. However, future studies will need to be performed to confirm this.

4.6 Conclusion

The main finding from this investigation is that the isovelocity squatting force-velocity relationship conforms to the typical *in-vivo* force-velocity profile with eccentric forces greater than isometric. The group mean normalised eccentric forces (1.1 times isometric) were similar to those reported previously for both multi-joint and single-joint movements. Inter-participant variability existed in the eccentric forces produced, with some participants producing eccentric forces up to 1.62 times isometric, but others half of that and not exceeding isometric (0.84

times isometric). Concentric strength and training age did not appear to determine the ability to maximise eccentric force production. The presented data from this chapter suggests that higher eccentric velocities result in greater force production, therefore practitioners may wish to select accentuated-eccentric loading protocols that permit safe application of a velocity of ~-0.5 $m.sec^{-1}$, or an eccentric tempo of ~1 second, if maximising eccentric force production is the objective of a training session. However, an assessment of eccentric capabilities may help to individualise training interventions, owing to the inter-participant variability in eccentric force production.

Chapter 5.

An Investigation of Movement Dynamics and Muscle Activity During Traditional and Accentuated-Eccentric Squatting

5.1 Abstract

Introduction Accentuated-eccentric loading takes advantage of the high force producing potential of eccentric muscle contractions, potentially maximising mechanical tension within the muscle. However, evidence is lacking on how accentuated-eccentric loading squatting may load the involved musculature, limiting scientifically justified programming recommendations. The purpose of this study was to investigate the effects of concentric and eccentric loads on joint loading and muscle activity of the lower limbs.

Methods Nine resistance trained males (24 ± 2 years, 81.2 ± 8.6 kg, 178 ± 5 cm) performed traditional squatting (20-100% of concentric 1RM) and accentuated-eccentric loading squatting with eccentric loads (110-150% of 1RM). Kinetics and kinematics of the hip, knee, and ankle joints were collected, with electromyography from the gluteus maximus, vastus lateralis, biceps femoris, and gastrocnemius medialis. A secondary cohort underwent a kinematic and electromyography analysis of squatting technique to compare Kineo and back and front barbell squatting.

Results Knee joint peak eccentric moments occurred at 120% 1RM (P=0.045), with no further increase thereafter. As eccentric load increased, the time course of moment development occurred earlier in the eccentric phase. This resulted in a 37% increase in eccentric knee extensor work from the 80% 1RM trial to the 120% 1RM trial (P<0.001). Neither hip nor ankle joints displayed further change in kinetics as eccentric load increased above 100% 1RM. Electromyographic activity during traditional squatting was ~15-30% lower in all eccentric trials than in concentric trials for all muscles. EMG plateaued between a load of 80-100% 1RM during the eccentric trials and did not increase with accentuated-eccentric loading. No significant differences in kinematics were found between Kineo and barbell squatting.

Conclusions The knee extensors appear to be preferentially loaded during accentuated-eccentric loading squatting. The greater work performed during the eccentric phase of the squat

as eccentric load increased suggests greater total mechanical tension could be the cause of adaptations from AEL. Our data suggest that accentuated-eccentric loading should be programmed with a load of 120% of 1RM. Further studies are needed to confirm the longer-term training effects of accentuated-eccentric loading.

5.2 Introduction

Increasing muscle force producing capacity is a primary goal for S&C practice, as it can improve performance in a wide range of sporting activities (Weyand et al., 2000, Barker et al., 2018). Enhanced force production can be achieved by increased neural drive and the addition of contractile material via skeletal muscle hypertrophy (Folland and Williams, 2007), both of which can be achieved with resistance training (Balshaw et al., 2017).

One of the primary mechanisms that drives resistance training adaptation within the muscle is mechanical tension (Wackerhage et al., 2018). It is known that the tension/force that is produced during ex-vivo muscular contraction produces a dose response relationship with the activation of the muscle hypertrophy pathway (mTORC1) (Rindom et al., 2019). However, it has been shown that strength-trained populations have an attenuated response to resistance training (Ahtiainen et al., 2003). Thus S&C practitioners seek advanced training methods to facilitate continued adaptation, often by increasing the mechanical tension placed upon a muscle. One such advanced training method is done by manipulating the loading during eccentric phase of resistance training (Suchomel et al., 2019a).

As discussed in the literature review in chapter two, greater maximal forces are produced during eccentric muscle contraction, with the magnitude of the eccentric force being dependent on the conditions of measurement, with forces up to 80% greater in isolated muscle (Edman, 1988), and forces/moments up to 30% greater for single-joint movements (Hahn, 2018), and

10% greater during multi-joint exercises (see chapter four). These differences are likely due to an eccentric-specific neural activation strategy (Duchateau and Enoka, 2016), and differences in neural activity during multi-joint movements (Behm et al., 2003). To that end, the question arises whether sufficiently greater muscular forces are actually achieved during eccentric training, as it is prescribed within applied practice (i.e., not under isovelocity conditions) to warrant the complexity of these training designs.

During traditional (TRAD) squatting (i.e., same absolute load for the concentric and eccentric phase), GRFs have been reported to be greater during the concentric phase than during the eccentric phase (Swinton et al., 2012), given the load must be accelerated against gravity in the concentric phase. Consequently, the load during the eccentric phase in TRAD squatting is significantly below the maximum eccentric capacity, potentially under-loading the musculature and therefore providing sub-optimal mechanical tension to promote adaptation. However, the degree of this under-loading during the eccentric phase compared to the concentric phase is currently unknown.

One eccentric resistance training method that shows promise for overcoming the above limitations of TRAD squatting is accentuated-eccentric loading (Harden et al., 2020b), whereby the load is greater during the eccentric phase than the concentric. By taking advantage of the direction-specific mechanical properties of muscle contraction, accentuated-eccentric loading may increase the peak and volume of mechanical tension experienced. Previous literature has presented evidence supporting the use accentuated-eccentric loading in strength-trained populations (see chapter 2), with increases in both strength and hypertrophy (Suchomel et al., 2019a), as well as maintained acute endocrine responses (Walker et al., 2017). Thus, many elite S&C practitioners now adopt accentuated-eccentric loading into their training repertoire (Harden et al., 2020a). However, there is a dearth of information regarding how best to program accentuated-eccentric loading, especially considering a systematic review from

2017 found ~80% of eccentric research has been performed using single-joint methodologies (Douglas et al., 2017), whereas multi-joint movements are typically used in applied practice (e.g., squatting). Subsequently, due to the lack of research it is difficult to produce scientifically justified accentuated-eccentric loading training recommendations.

As was discussed in chapter two, accentuated-eccentric loading may overcome the limitations of underloading the eccentric phase. Harden *et al.,* (2018b) explored the issue of eccentric under-loading using a pneumatic leg-press to deliver loads equivalent to 110, 130, & 150% of isometric force, and found that a greater eccentric load results in an increase in eccentric GRF (Harden et al., 2018b). Likewise, Sarto *et al.,* (2020) demonstrated that an accentuated-eccentric load of 150% during a leg-press results in a 31% increase in quadriceps muscle activity compared to a TRAD eccentric load of 80% of 1RM. Taken together, these studies indicate a greater loading of the lower limb musculature during accentuated-eccentric loading. However, it is uncertain how this would translate to squatting, due to the differences in kinematics and muscle activity between the squat and leg-press (Escamilla et al., 2001). One of the few studies that has examined the eccentric phase of the squat with accentuated-eccentric loading (Wagle et al., 2021) found that this resulted in a ~9% greater eccentric work. Unfortunately, this was only assessed with one accentuated-eccentric load (105% of concentric 1RM) and did not investigate individual joint kinetics (Wagle et al., 2021), and therefore comprehensive training recommendations cannot be established.

In order to produce comprehensive training recommendations for accentuated-eccentric loading in squatting, it is necessary not only to understand the total load that can be lifted, but also to understand the joint contributions, as not all joints are loaded equally during multi-joint movements. Additionally, the loading experienced in each phase of the squat may vary due to changes in squatting technique. During the eccentric phase athletes may alter their strategy to control the load and may not produce maximum effort throughout the full range of descent (van den Tillaar, 2019), and thus descent velocity can vary (Miletello et al., 2009). These changes may affect joint work and the peak joint moments that are produced by the lower limb muscles, with work being an indicator of the total volume of mechanical tension, and peak joint moment an indicator of peak mechanical tension experienced by a muscle. Therefore, in order to identify optimal accentuated-eccentric loading protocols, a range of accentuated-eccentric loads needs to be assessed. Application of squatting loads greater then 1RM can be risky and challenging, or requires specialist equipment such as the Kineo, which has been demonstrated in chapter three to be safe and effective for this purpose.

Therefore, the primary objectives of this study were to study the application of accentuated-eccentric loading during squatting and to: 1) determine how the eccentric joint moments and work of the lower limb joints change with the magnitude of eccentric load; 2) determine how the concentric and eccentric joint moments and work of the lower limbs differed during TRAD loading; 3) establish whether/how lower limb peak joint moments and work from the accentuated-eccentric loading trials differ from those achieved during commonly prescribed TRAD loads used for resistance training. Secondary objectives were to investigate whether any changes in joint moments and work are accompanied by changes in muscle activity or changes in joint kinematics.

It was hypothesised that: 1) as eccentric load increased, the joint moment and work of the lower limbs would increase; 2) concentric joint moments and work of the lower limbs would be greater than eccentric joint moments and work during TRAD loading; 3) eccentric joint moments and work during accentuated-eccentric loading would exceed those during the concentric phase of TRAD; and 4) an increased joint moment would be accompanied by an increase in EMG activity.

5.3 Methods

Participants: Nine male participants were recruited for this study (age; 24 ± 2 years, body mass; 81.2 ± 8.6 kg, height; 178 ± 5 cm). This sample size exceeded the minimum participant sample size (n = 7) determined using joint moment data from previous research (Flanagan and Salem, 2008) with power and alpha levels set to 0.8 and 0.05, respectively. All participants had completed at least twelve months of resistance training prior to this study and had a mean relative barbell back squat 1RM of 1.71 ± 0.17 body mass. Prior to commencement, participants were informed of the study procedures and gave written informed consent. The study was approved by the Liverpool John Moores University research ethics committee (19/SPS/038).

Experimental protocol: All squatting trials (both TRAD and accentuated-eccentric loading) were performed on the Kineo, which was described in chapter three. Participants reported to the Liverpool John Moores laboratories on three occasions. The first visit was used for familiarisation to the Kineo and accentuated-eccentric loading squatting. During the second visit, each participant's concentric 1RM squat on the Kineo was measured. Experimental data were collected on the third visit, consisting of kinetics, 3D kinematics and electromyography (EMG) during TRAD and accentuated-eccentric loading. Each session began with a standardised warmup following the RAMP protocol (Jeffreys, 2006). For more details on this warmup, please refer to the appendices section.

Familiarisation and squat set up: Participants were fitted with a shoulder/hip harness, adjusted for goodness of fit, before being attached to the Kineo via a cable (Figure 4-1). Range of motion was determined, so that the eccentric phase commenced until the participant had squatted down to a depth at which the top of the thighs where parallel to the ground. An audible signal was given when this depth was attained and confirmed via 3D motion analysis. The concentric phase began immediately after the end/completion of the eccentric phase and until the participant had fully extended the hips and knees. The corresponding cable positions were programmed and saved within the Kineo software control system to facilitate automatic load changes for accentuated-eccentric loading squatting during the experimental testing. Participants finished the familiarisation session with several sets of TRAD and accentuated-eccentric loading squatting ranging from 20-150% of estimated concentric 1RM, to become familiar with the automatic load adjustments during accentuated-eccentric loading.

One-repetition maximum testing: Participants reported to the laboratories in a fed and hydrated state. Body mass (± 0.1 kg) and height (± 0.5 cm) were measured (SECA 704/202, Germany). Participants then performed a standardised warmup, finishing with several progressively heavier squats on the Kineo. Following protocols of the National Strength and Conditioning Association (Haff and Triplett, 2015) participants were allowed a maximum of five attempts to establish a TRAD squatting 1RM using the Kineo, adhering to the technique outlined in the familiarisation, with 3-5 minutes passive rest between attempts.

Kinetic, kinematic, and electromyography testing*:* On the third visit (5-7 days post 1RM), participants reported to the laboratory at a similar time of day to that at which they performed the 1RM testing. Upon completion of the standardised warmup, participants were fitted with reflective markers and surface electromyography electrodes (BlueSensor, Ambu, Denmark).

Thirty-six spherical reflective markers were used to define and track the lower limb segments. This included a modified CODA pelvis marker set to define the pelvis segment with additional tracking markers on the iliac crest to aid in pelvis tracking and to overcome ASIS marker occlusion during deep hip flexion. The remaining markers were placed on the lateral & medial femoral epicondyles, lateral & medial malleoli, heel, and 1st & 5th metatarsals to define the thigh, shank, and foot segments. Additionally, rigid four-marker cluster sets were placed on the lateral thighs and shanks to aid in thigh and shank tracking. Joint centres of the hip and knee were identified by functional movement trials that isolated movements of those joints, and were calculated using the Gillette algorithm (Schwartz and Rozumalski, 2005). Surface electromyography electrodes were placed on the gluteus maximus, vastus lateralis, biceps femoris, and gastrocnemius medialis according to the SENIAM guidelines (Hermens et al., 1999). Prior to electrode placement, the skin was prepared by shaving and abrading to enhance signal quality.

Participants performed ten trials of squatting (five TRAD, five accentuated-eccentric loads) in a randomised order. TRAD squatting applied the same absolute load for both the concentric phase and eccentric phase (20%, 40%, 60%, 80%, and 100% 1RM). Accentuated-eccentric loading squatting applied an increased load (compared to concentric 1RM) in the eccentric phase (110%, 120%, 130%, 140%, and 150% 1RM) whilst the concentric load remained at 60% 1RM for all accentuated-eccentric loading trials. A load of 60% 1RM was chosen for the concentric trials based upon pilot testing, as it enabled enough preload to enable maximal eccentric contractions (Hahn, 2018), whilst minimising excess fatigue. Load adjustment between the eccentric and concentric phase for accentuated-eccentric loading trials was performed automatically by the Kineo once the programmed transition point had been reached. All trials were performed with three repetitions, interspersed by five minutes passive recovery. The average of the three trials was used for data analyses.

Data acquisition and analyses: During all trials, GRFs were collected from two force plates sampling at 1500 Hz (9287c, Kistler, Switzerland), amplified (9865, Kistler, Switzerland) and converted to a digital signal. Reflective markers were tracked at 200 Hz using six 3D motion capture cameras (Opus 3 series, Qualisys, Sweden). Electromyographic signals were sampled at 1500 Hz and transmitted wirelessly (Research DTS, Noraxon, USA). All force, motion and EMG data were recorded synchronously in Qualisys Track Manager (Qualisys, Sweden), before being exported to Visual 3D (C-Motion, USA) for analyses. Force and motion data were processed with a lowpass 4th order Butterworth filter, with a cut off frequency of 6 Hz. EMG data was band pass filtered between 10 and 250 Hz and root mean squared with a moving average of 100 ms.

Joint range of motion (°) and joint velocity ($°\cdot s^{-1}$) during the concentric and the eccentric phases were quantified. Inverse dynamics calculations were used to calculate joint moments of the hip, knee and ankle during the concentric and eccentric phases of the squat, which were normalised to body mass ($N\cdot m\cdot kg^{-1}$). Integration of the joint power curve allowed for the calculation of eccentric and concentric joint work (J). Joint work was reported as an absolute magnitude, irrespective of direction (+ or -) for ease of comparison and graphical representation. Electromyography data were analysed for peak EMG, and total integrated EMG of the eccentric and concentric phases of each joints individual range of motion. All EMG data were normalised to the equivalent measure obtained during the concentric TRAD 100% trial.

Statistical analyses: Mauchly's test for sphericity, Levene's test for homogeneity of variance, and Shapiro-Wilk's test for normality were performed on all data. Greenhouse-Geisser corrections were used on data that violated the assumption of sphericity. All data were normally distributed ($P = 0.145$ to 0.814) and had a homogeneity of variance ($P = 0.157$ to 0.987). To assess study objective one, a one-way repeated measures ANOVA was used to determine if eccentric load (20 to 150% 1RM) had an effect on the kinetics, kinematics, and muscle activity during the eccentric phase of the squat. To assess study objective two, a two-way repeated measures ANOVA was used to compare the kinetics, kinematics, and muscle activity during the concentric and eccentric phase of the squat during TRAD loading (20 to 100% 1RM). Study objective three was subsequently assessed with a one-way repeated measures ANOVA to compare the joint moment and work from the accentuated-eccentric loading trials that lead to the greatest eccentric kinetics to the concentric 80% and 100% trials. Bonferroni post-hoc analyses were used in all tests where appropriate. Effect sizes were calculated for all ANOVA tests using ω^2, with values of 0.01, 0.06, and 0.14 indicating a small, medium and large effect size, respectively (Field, 2013). Additionally, a paired-samples t-test was used to perform a comparison between the 80% 1RM and 120% 1RM trial. A Cohen's *d* effect size was calculated with values of 0.2, 0.5, and 0.8 representing a small, medium, and large effect size, respectively.

Coefficient of variation (CV) was used to identify repetition-to-repetition reliability. Peak joint moment (CV = 2.6 to 4.1%), joint work (CV = 1.8 to 2.4%), joint velocity (CV = 4.7 to 5.2%) and EMG (CV = 7.2 to 18.6%) had acceptable reliability and were similar to previous literature (Flanagan and Salem, 2008). For all data, statistical significance was assessed with an alpha level of 0.05. All analyses were performed in Statistical Package for the Social Sciences (SPSS version 27, IBM, USA).

5.4 Results

There was a significant effect of loading condition on the peak joint moments in the eccentric phase for the hip ($F = 2.773$, $P = 0.007$, $\omega^2 = 0.17$) (Figure 5-1A) and knee ($F = 16.408$, $P < 0.001$, $\omega^2 = 0.61$) (Figure 5-1B), but not on the ankle ($F = 0.254$, $P = 0.985$, $\omega^2 = -0.08$) (Figure 5-1C). Post-hoc testing revealed that there was a plateau in peak eccentric moment at a load of 80% 1RM for the hip ($P = 0.039$), and at 120% 1RM for the knee ($P = 0.045$).

Analyses of eccentric joint work found that there was a significant effect of loading on the hip ($F = 2.1$, $P = 0.037$, $\omega^2 = 0.02$) (Figure 5-1D) and on the knee ($F = 5.438$, $P < 0.001$, $\omega^2 = 0.31$) (Figure 5-1E), with no effect or ankle ($F = 0.171$, $P= 0.996$, $\omega^2 = -0.09$) (Figure 5-1F). Post-hoc testing of the eccentric hip and knee work revealed a plateau at a load of 80% ($P = 0.023$) and 120% ($P = 0.022$) of 1RM, respectively.

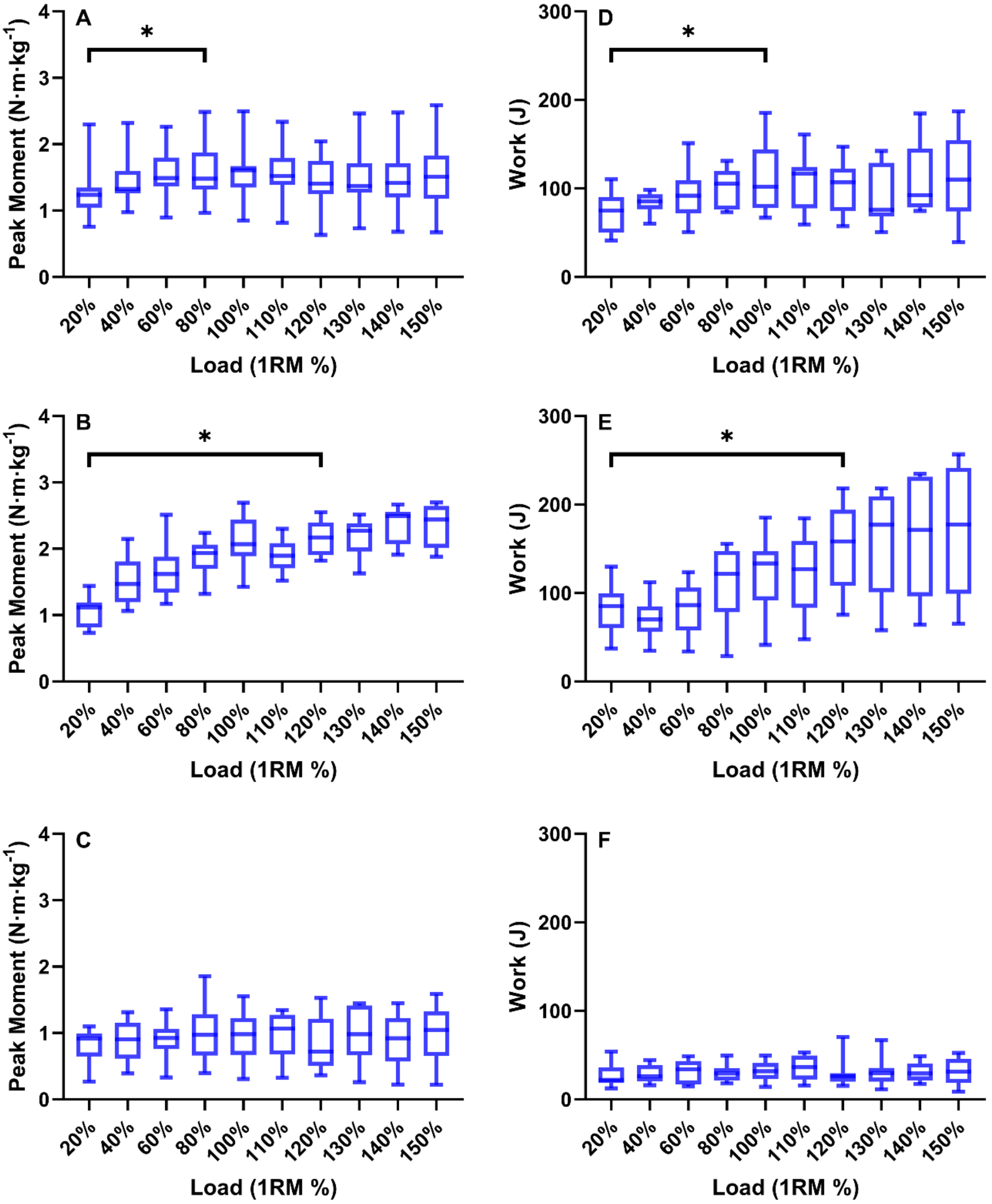

*Figure 5-1 Box-plots (median ± IQR) displaying the eccentric peak moment (N·m·kg-1) and work (J) for the hip (A and D), knee (B and E), and ankle extensors (C and F) during the eccentric phase of the squat with an external load of 20-150% 1RM. * = significant increase ($P < 0.05$) (n = 9).*

During TRAD squatting, the peak joint moments were greater in the concentric than eccentric phase for the hip (F = 3.982, $P = 0.049$, $\omega^2 = 0.03$), knee (F = 24.729, $P < 0.001$, $\omega^2 = 0.13$) and ankle (F = 3.691, $P = 0.044$, $\omega^2 = 0.03$) (Figure 5-2A-C). Similarly, joint work was greater in the concentric than eccentric phase for the hip (F = 3.783, $P = 0.045$, $\omega^2 = 0.02$) and knee (F = 31.58, $P < 0.001$, $\omega^2 = 0.19$). However, no difference was found between the concentric and eccentric ankle work (F = 0.819, $P = 0.368$) (Figure 5-2D-F). Post-hoc analyses identified that the concentric and eccentric knee extension peak moment and work increased with load up to 100% 1RM ($P = 0.003$). Concentric and eccentric hip extension moment and work did not significantly increase past 60% ($P = 0.039$), and the ankle extensors saw no effect of loading on either peak moment or work for either the concentric or eccentric phase ($P = 0.084$).

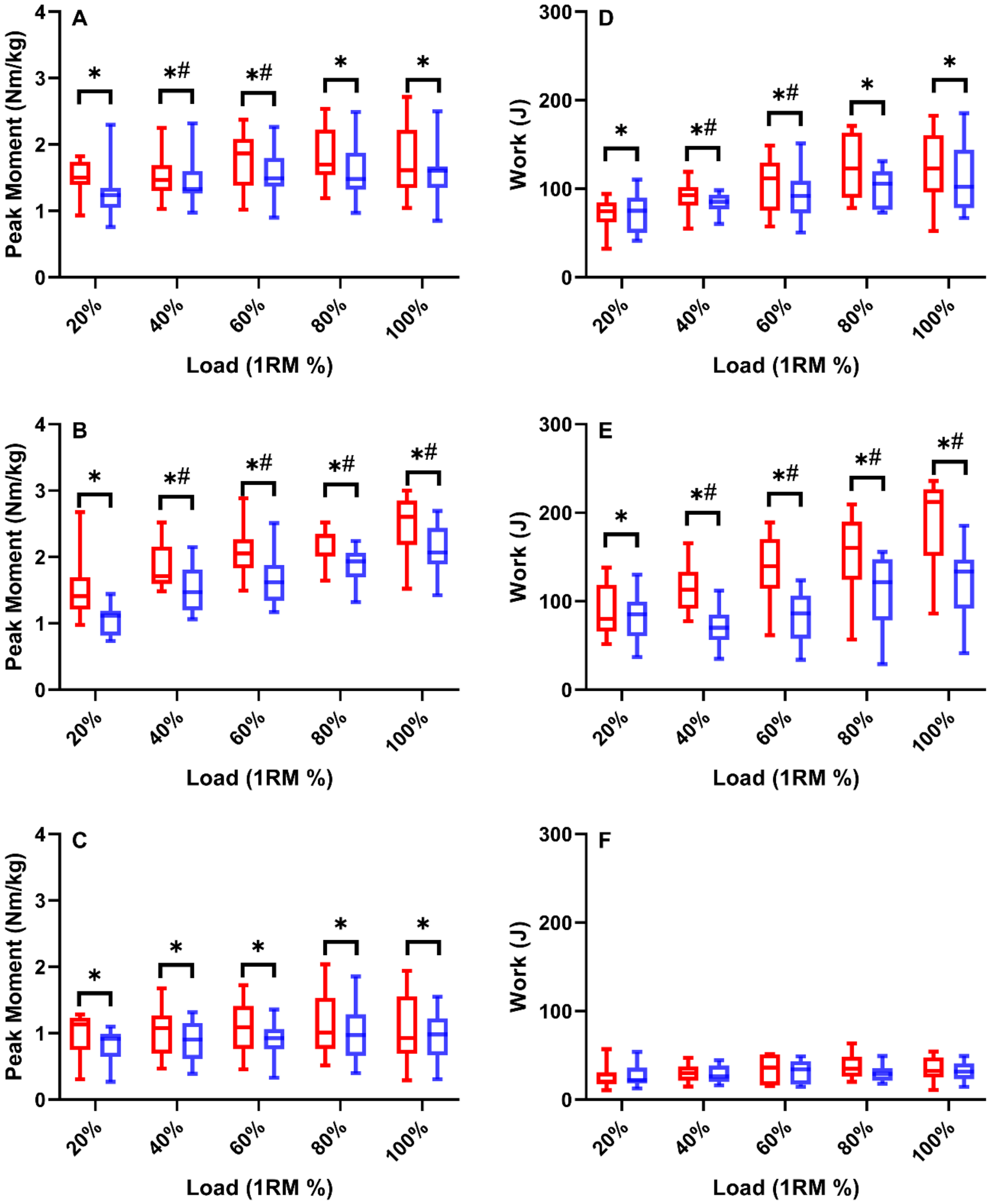

*Figure 5-2 Box-plots (median ± IQR) displaying the concentric (red bars) and eccentric (blue bars) peak moment (N·m·kg-1) and work (J) for the hip (A and D), knee (B and E), and ankle extensors (C and F) during TRAD (20-100%) squatting. * = Eccentric joint kinetics (moment or work) is statistically smaller (P < 0.05) than concentric joint kinetics at the same given load. # = Joint Kinetics is statistically different (P < 0.05) to the preceding trial (n = 9).*

As both eccentric knee moment and work plateaued at 120%, these data were compared to the concentric knee moments and work at 80% and 100% (moment: F = 2.775, $P = 0.05$, $\omega^2 = 0.1$, work: F = 2.251, $P = 0.125$, $\omega^2 = 0.08$). It was found that peak knee moment in the eccentric phase of the accentuated-eccentric loading 120% trial was significantly less than in the concentric phase of 100% ($P = 0.042$), but not significantly different from concentric 80% trial ($P = 0.839$). Eccentric knee work at 120% was significantly greater than at 80% ($t = -6.444$, $P < 0.001$, Cohen's *d* effect size = 0.81) (Figure 5-3).

The knee moment-time graphs during the eccentric phase (normalised to eccentric phase duration) (Figure 5-3) reveal changes in the time course of moment development as load increased, which helps to explain the effects of load on peak moment and work during the accentuated-eccentric loading trials. As external load increased from 80% to 120% 1RM, eccentric knee extensor peak moment increased (17%) and then plateaued, with a distinct peak occurring towards the end of the range of motion. Furthermore, with each increase in load, moment development in the first half of the movement was greater, resulting in a 37% increase in work from the 80% 1RM trial to the 120% 1RM trial (Figure 5-3).

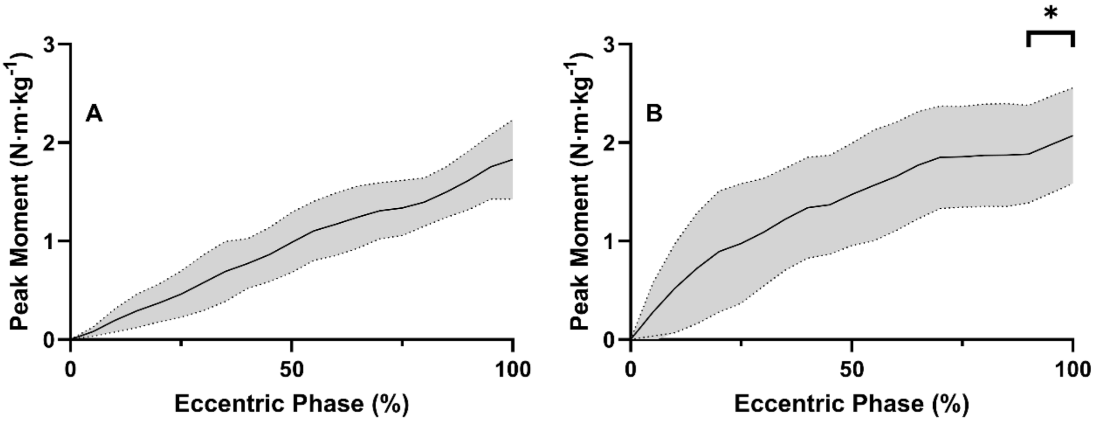

*Figure 5-3 Mean ± SD eccentric knee extension moment (N·m·kg-1) over the eccentric phase duration (%) graph, demonstrating the increase in early rate of moment development as eccentric load increased from 80% 1RM (A), to 120% 1RM (B). * = significant increase (P < 0.05) in peak moment (n = 9).*

Analyses of EMG activity identified greater peak magnitudes during concentric than eccentric phases during TRAD squatting across all loads; gluteus maximus (F = 51.952, $P < 0.001$, $\omega^2 = 0.58$), vastus lateralis (F = 29.81, $P < 0.001$, $\omega^2 = 0.27$), biceps femoris (F = 20.852, $P = 0.002$, $\omega^2 = 0.35$), and gastrocnemius medialis (F = 18.545, $P < 0.001$, $\omega^2 = 0.14$) (Figure 5-4). Additionally, eccentric loading had an effect on EMG activity, with an increase in activity as load increased up to 100% for the gluteus maximus (F = 4.069, $P < 0.001$, $\omega^2 = 0.23$), 80% for the vastus lateralis (F = 2.165, $P = 0.033$, $\omega^2 = 0.10$) and biceps femoris (F = 2.754, $P = 0.007$, $\omega^2 = 0.14$), whilst there was no effect of load on the gastrocnemius medialis activity (F = 1.00, $P = 0.447$) (Figure 5-5).

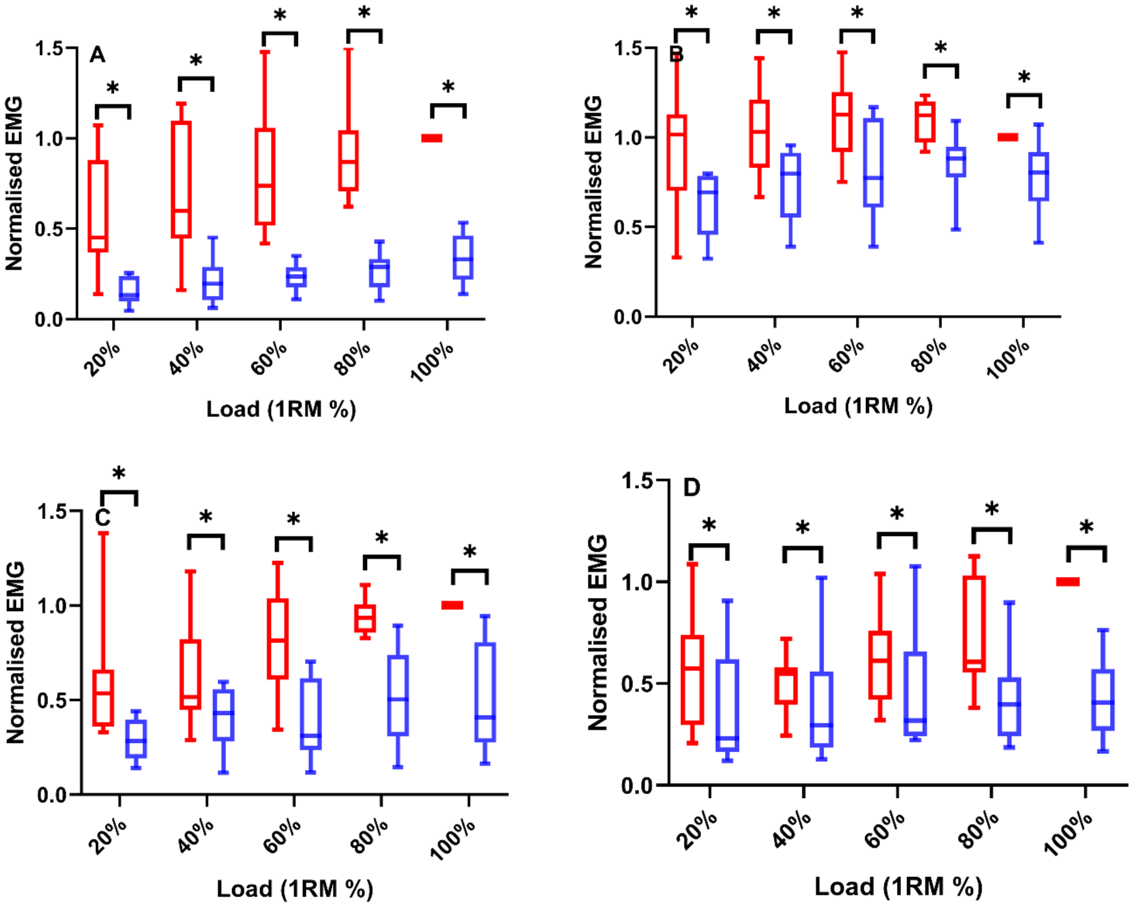

*Figure 5-4 Box-plots (median ± IQR) displaying the concentric (red bars) and eccentric (blue bars) normalised EMG for the gluteus maximus (A), vastus lateralis (B), biceps femoris (C) and gastrocnemius medialis (D) during TRAD (20-100%) squatting. * = Eccentric muscle activity is significantly smaller ($P < 0.05$) than concentric muscle activity at the same given load (n = 9).*

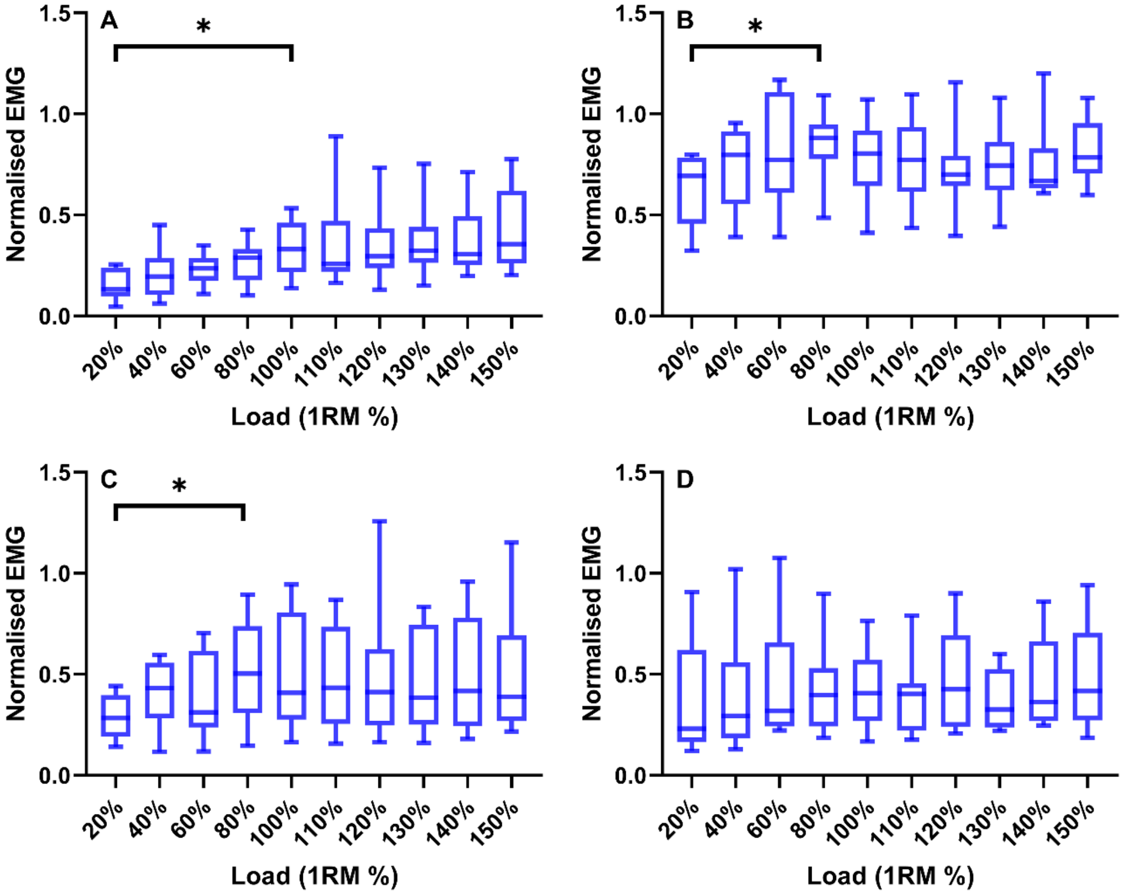

*Figure 5-5 Box-plots (median ± IQR) displaying the eccentric normalised EMG for the gluteus maximus (A), vastus lateralis (B), biceps femoris (C) and gastrocnemius medialis (D) during the eccentric phase of the squat with an external load of 20-150% 1RM. * = significant increase ($P < 0.05$) ($n = 9$).*

The joint angular ranges of motion kinematics did not differ between loads for the hip (F = 0.274, *P* = 0.98), knee (F = 0.276, *P* = 0.979), or ankle joints (F = 0.155, *P* = 0.998) (Table 5-1). The joint angle at which the peak moment occurred, during both the concentric and eccentric phases, was not different between loads for the hip (F = 7.03, *P* = 0.426), knee joints (F = 5.228, *P* = 0.052), or ankle joint (F = 0.610, *P* = 0.658). However, the peak concentric ankle joint moment occurred in a significantly more dorsi-flexed position than the peak eccentric moment (34 ± 1° vs 26 ± 1°) (*P* = 0.006) (Table 5-1). Lastly, concentric joint angular velocity was greater for all joints, at all loads, than eccentric joint angular velocity (Table 5-2).

For the hip (F = 17.219, $P < 0.001$), velocity during concentric and eccentric phases reduced as load increased up to 80% 1RM, after which it plateaued. Similar results were found for the ankle (F = 8.516, $P < 0.001$) with a plateau after 60%. However, the knee joint angular velocity only showed a plateau after 100% 1RM (F = 22.837, $P < 0.001$). There was no further decrease in angular velocity as eccentric load increased above 100% ($P = 0.698$ to 0.99).

*Table 5-1 Joint angle kinematics (mean ± SD) for the hip, knee, and ankle joints during the concentric and eccentric phases of the squat with external loads ranging from 20% to 150% of concentric one-repetition maximum. * = Joint angle during the eccentric phase is statistically smaller (P < 0.05) than during the concentric phase at the same given load (n = 9).*

			Loading Condition (percentage of concentric one-repetition maximum) (%)									
			20%	40%	60%	80%	100%	110%	120%	1305	140%	150%
Joint Angle at Peak Moment (°)	Hip	Concentric	84 ± 17°	83 ± 18°	76 ± 16°	79 ± 14°	81 ± 13°					
		Eccentric	80 ± 11°	86 ± 14°	86 ± 11°	86 ± 11°	77 ± 10°	77 ± 13°	74 ± 12°	77 ± 14°	77 ± 10°	80 ± 14°
	Knee	Concentric	102 ± 11°	104 ± 10°	101 ± 7°	101 ± 8°	99 ± 14°					
		Eccentric	104 ± 10°	107 ± 9°	105 ± 6°	105 ± 10°	103 ± 10°	101 ± 8°	102 ± 9°	98 ± 7°	101 ± 9°	103 ± 9°
	Ankle	Concentric	37 ± 3°	36 ± 4°	34 ± 4°	32 ± 5°	30 ± 4°					
		Eccentric	*23 ± 7°	*26 ± 12°	*24 ± 8°	29 ± 9°	*27 ± 8°	25 ± 7°	23 ± 7°	23 ± 7°	26 ± 9°	23 ± 5°
Range of Motion (°)		Hip	89 ± 12°	93 ± 14°	91 ± 9°	93 ± 11°	89 ± 10°	88 ± 10°	89 ± 10°	88 ± 10°	90 ± 10°	90 ± 10°
		Knee	112 ± 8°	112 ± 8°	111 ± 8°	111 ± 9°	108 ± 6°	108 ± 8°	109 ± 8°	108 ± 7°	109 ± 8°	110 ± 8°
		Ankle	41 ± 3°	40 ± 3°	40 ± 2°	40 ± 3°	40 ± 3°	40 ± 3°	40 ± 3°	40 ± 2°	40 ± 2°	40 ± 3°

*Table 5-2 Joint angular velocity kinematics (mean ± SD) for the hip, knee, and ankle joints during the concentric and eccentric phases of the squat with external loads ranging from 20% to 150% of concentric one-repetition maximum. * = eccentric angular velocity is statistically slower ($P < 0.05$) than concentric angular velocity at the same given load. # = Angular velocity is statistically different ($P < 0.05$) to the preceding trial ($n = 9$).*

			Loading Condition (percentage of concentric one-repetition maximum) (%)									
			20%	40%	60%	80%	100%	110%	120%	1305	140%	150%
Peak Angular Velocity (°·s^{-1})	Hip	Concentric	200 ± 83°·s^{-1}	#180 ± 65°·s^{-1}	#194 ± 66°·s^{-1}	#182 ± 57°·s^{-1}	185 ± 55°·s^{-1}					
		Eccentric	*91 ± 30°·s^{-1}	*#113 ± 41°·s^{-1}	*#81 ± 17°·s^{-1}	*#102 ± 29°·s^{-1}	*84 ± 27°·s^{-1}	77 ± 35°·s^{-1}	80 ± 22°·s^{-1}	80 ± 30°·s^{-1}	79 ± 23°·s^{-1}	74 ± 22°·s^{-1}
	Knee	Concentric	257 ± 74°·s^{-1}	#251 ± 62°·s^{-1}	#260 ± 62°·s^{-1}	#250 ± 55°·s^{-1}	256 ± 42°·s^{-1}					
		Eccentric	*126 ± 26°·s^{-1}	*#142 ± 43°·s^{-1}	*#116 ± 32°·s^{-1}	*115 ± 32°·s^{-1}	*#101 ± 31°·s^{-1}	#91 ± 25°·s^{-1}	98 ± 25°·s^{-1}	95 ± 28°·s^{-1}	104 ± 29°·s^{-1}	97 ± 28°·s^{-1}
	Ankle	Concentric	107 ± 41°·s^{-1}	#102 ± 23°·s^{-1}	103 ± 25°·s^{-1}	101 ± 28°·s^{-1}	105 ± 26°·s^{-1}					
		Eccentric	*48 ± 16°·s^{-1}	*#57 ± 16°·s^{-1}	*#49 ± 13°·s^{-1}	*46 ± 12°·s^{-1}	*40 ± 11°·s^{-1}	36 ± 8°·s^{-1}	38 ± 11°·s^{-1}	38 ± 11°·s^{-1}	43 ± 12°·s^{-1}	39 ± 9°·s^{-1}
Average Angular Velocity (°·s^{-1})	Hip	Concentric	94 ± 29°·s^{-1}	#86 ± 24°·s^{-1}	#77 ± 18°·s^{-1}	#68 ± 17°·s^{-1}	#60 ± 12°·s^{-1}					
		Eccentric	*52 ± 15°·s^{-1}	*#57 ± 20°·s^{-1}	*#48 ± 15°·s^{-1}	*#44 ± 13°·s^{-1}	*41 ± 13°·s^{-1}	39 ± 40°·s^{-1}	42 ± 15°·s^{-1}	38 ± 14°·s^{-1}	40 ± 17°·s^{-1}	41 ± 16°·s^{-1}
	Knee	Concentric	128 ± 28°·s^{-1}	#117 ± 21°·s^{-1}	#107 ± 16°·s^{-1}	#92 ± 14°·s^{-1}	#79 ± 14°·s^{-1}					
		Eccentric	*74 ± 18°·s^{-1}	*#79 ± 21°·s^{-1}	*#69 ± 16°·s^{-1}	*#63 ± 16°·s^{-1}	*#57 ± 16°·s^{-1}	55 ± 18°·s^{-1}	60 ± 20°·s^{-1}	54 ± 20°·s^{-1}	56 ± 24°·s^{-1}	53 ± 23°·s^{-1}
	Ankle	Concentric	36 ± 10°·s^{-1}	#32 ± 5°·s^{-1}	#30 ± 5°·s^{-1}	#26 ± 4°·s^{-1}	24 ± 5°·s^{-1}					
		Eccentric	*19 ± 4°·s^{-1}	*21 ± 4°·s^{-1}	*19 ± 3°·s^{-1}	*18 ± 3°·s^{-1}	*17 ± 5°·s^{-1}	17 ± 4°·s^{-1}	18 ± 5°·s^{-1}	16 ± 5°·s^{-1}	16 ± 6°·s^{-1}	16 ± 5°·s^{-1}

5.5 Discussion

In this study the joint kinetics, mechanical loading and kinematic characteristics of traditional and accentuated-eccentric loading squatting were established. Supporting the first hypothesis, it was identified that peak eccentric knee extensor moments occurred at 120% of 1RM, plateauing with further increases in external squat load. The hip and ankle extensors showed no increase above 100% 1RM in eccentric joint moment or work during accentuated-eccentric loading squatting. Although only small increases in peak knee joint moment were observed, eccentric moment development occurred earlier during the eccentric phase as eccentric load increased (Figure 5-3), contributing to a significant increase in knee joint work up to 120% of 1RM. Furthermore, the vastus lateralis appears to experience the greatest eccentric EMG activity (Figure 5-4/Figure 5-5) (relative to concentric 1RM activity). However, our third hypothesis is rejected as the eccentric joint moments did not exceed the concentric joint moments, with the 120% of 1RM trial eccentric knee joint moment being smaller than the 10% 1RM trial concentric knee joint moment.

The first aim of this study was to identify whether increased squat loading would result in an increased eccentric joint moment and work. This first hypothesis can be accepted, since there was an increase in both knee extensor moment and work as eccentric load increased with a plateau in knee extensor moment occurring at 120% 1RM, and a plateau in hip extensor moment occurring at 80% 1RM. During TRAD loading the relative contribution (as determined by the eccentric joint work divided by the sum of joint works) of the hip, knee and ankle extensors were 0.42 ± 0.09, 0.46 ± 0.12, and 0.12 ± 0.03 respectively. However, as load increased to 120% 1RM the relative contributions were 0.35 ± 0.09, 0.55 ± 0.12, and 0.11 ± 0.04, suggesting a preferential loading on the knee extensors during accentuated-eccentric loading. This contrasts with what is known about the concentric phase of squatting, in which the hip extensor moment increases to a greater extent than the knee extensors as load is increased (Farris et al., 2016, Flanagan and Salem, 2008). Although this may be explained by differences in kinematics and muscle activity, there was no findings changes in joint ranges of motion or velocities as eccentric load increased above 100% (i.e., accentuated-eccentric loading). However, during heavy concentric squatting (70% 1RM) the forwards inclination of the trunk can increase by ~16° compared to lighter loads (30% 1RM) (Kellis et al., 2005), increasing the moment arm of the centre of mass about the hips and reducing the moment arm at the knee, explaining joint-specific contributions in those studies (Flanagan and Salem, 2008, Farris et al., 2016). Therefore, in the present study it could be that the preferential loading of the knee extensors during accentuated-eccentric loading is a result of the participants having not altered their kinematics and joint dynamics with increasing eccentric load by keeping the trunk more vertical. The preferential loading at the knee during accentuated-eccentric loading squatting is further supported by the EMG data (Figure 5-5) which is consistent with previous literature (Luera et al., 2014) showing EMG activity of the hip extensors is lower than the activity of the knee extensors during eccentric squatting.

However, caution must be taken when extrapolating the result of this study to barbell squatting. It was demonstrated in chapter three that the barbell and Kineo squat have similar kinematics and muscle activity in the lower limbs under traditional loading conditions. For this data to be transferable to barbell squatting, the participants must be able to maintain their kinematics during the eccentric phase during accentuated-eccentric loading, which may be a more complex movement pattern due to the high centre of mass with the barbell being positioned on the posterior deltoids. Therefore, accentuated-eccentric loading squatting may only be applicable to well-trained individuals.

Supporting the second hypothesis, the joint moments in the concentric phase were 11-20% greater than in the eccentric phase (Figure 5-2). This difference was similar for the hip, knee and ankle extensors, therefore providing more evidence that during TRAD squatting the eccentric phase is underloaded and may therefore be sub-optimal as a training stimulus, considering peak eccentric ground reactions forces during isovelocity squatting are ~10% greater than concentric (Armstrong et al., 2022b) (see chapter four). Considering that account an increased eccentric load resulted in an increased eccentric knee moment and work for the knee extensors (Figure 5-1), accentuated-eccentric loading would be able to reduce the underloading that occurs during TRAD and can be recommended for inclusion in S&C practice.

In the present study, eccentric knee extensor peak moment plateaued after 120% 1RM (2.2 ± 0.3 $N \cdot m \cdot kg^{-1}$). However, this value was lower than the greatest concentric moment (2.5 ± 0.5 $N \cdot m \cdot kg^{-1}$ at 100% 1RM), suggesting that the underloading of the knee extensors is reduced, but not completely overcome during accentuated-eccentric loading squatting, thus the third hypothesis is rejected. There are several potential reasons for this. Firstly, the relative muscular contribution of the knee extensors during a squat is ~60% compared to their single-joint isometric maximum (Bryanton et al., 2012), which is partially explained by the low (<50%) muscle activity during a squat compared to single-joint maximum voluntary contraction (Yavuz et al., 2015). Considering that neural activity is lower during the eccentric phase compared to the concentric (Figure 5-4), the potential to produce a maximal knee extensor moment might be further reduced. These neural characteristics may therefore explain why eccentric joint moments did not exceed the concentric moments, even with accentuated-eccentric loading.

Although eccentric knee extensor moment was lower than concentric, it was hypothesised that EMG would increase as eccentric load and moment increased during accentuated-eccentric loading (Luera et al., 2014). However, the presented data (Figure 5-5) showed no significant differences in vastus lateralis EMG as loads increased above 80%, despite an increase in joint moment and work up to 120% 1RM. This suggests factors independent of the neural input, with a plausible explanation for this being related to the force producing potential of eccentric contractions, which benefits from the spring-like behaviour of the titin myofilament (Herzog, 2014). Therefore, the fourth hypothesis is rejected as the increased eccentric joint moments during accentuated-eccentric loading are accompanied by increased muscle activity.

5.5.1 Practical Implications

Although the greatest peak joint moments occurred during the concentric 100% 1RM, training volume also regulates the hypertrophic stimulus (Krieger, 2010) and greater eccentric work was performed during the accentuated-eccentric loading trials, which would facilitate a greater volume of mechanical tension. For example, comparing the eccentric work during the 120% trial to the eccentric work during a typical TRAD protocol for resistance training (e.g., 80% 1RM) would result in the knee joint experiencing an increase of 37% for eccentric work, as well as a 17% increase in the eccentric peak moment. A training load that maximises the joint moment, but also facilitates multiple repetitions at a high load is likely to optimise hypertrophy and strength gains. Therefore, according to the present study using the Kineo system, it appears this may be best achieved with accentuated-eccentric loading training, using a load of 120% 1RM during the eccentric phase of the squat.

This data suggests that the knee extensors are preferentially loaded during eccentric squatting, having experiencing greater peak moments, work, and muscle activity than the hip extensors. Therefore, squatting with accentuated-eccentric loading may benefit sporting activities that rely heavily on the knee extensors such as cycling (Aasvold et al., 2019), rowing (Baudouin and Hawkins, 2002), and sprinting (Dowson et al., 1998). Furthermore, accentuated-eccentric loading during squatting may elicit eccentric-specific adaptation in the form of an increased fascicle length (Timmins et al., 2016), and thus contraction velocity. As there appears to be a preferential loading of the quadriceps, these eccentric-specific adaptations may prove beneficial to changes of direction and braking ability (Colby et al., 2000), and injury prevention/rehabilitation of the knee (Lorenz and Reiman, 2011). Using the data collected in this study, future training intervention research should test whether these loading characteristics of accentuated-eccentric loading training translate into the hypothesised improvements in performance.

5.6 Conclusion

In conclusion, the knee extensors were preferentially loaded during eccentric squatting, and demonstrated increasing joint moment and work as eccentric load increased, with eccentric knee joint moment plateauing at 120% 1RM. However, despite eccentric contractions having the potential to produce the greatest joint moments, accentuated-eccentric loading squatting did not elicit an eccentric knee joint moment greater than the concentric joint moments produced during a 1RM. Increasing eccentric load resulted in a greater volume of work specifically in the earlier phase of the descent, which may in turn enhance the stimulus for hypertrophic and strength adaptation of the knee extensors. The data from this study suggests than an accentuated-eccentric load of 120% 1RM maximises knee extensor loading during the eccentric phase of squat with accentuated-eccentric loading. Future research will be needed to confirm if the greater loading results in increased training adaptations.

Chapter 6.

An Investigation of Athletic Performance and Muscle Function Improvements Following 6-weeks of Accentuated-Eccentric or Traditional Loading During the Squat

6.1 Abstract

Introduction During traditional resistance training (TRAD), the same absolute external loads are used during the concentric & eccentric phase of an exercise. However, greater forces can be produced during maximal eccentric contractions than maximal concentric contractions. Despite this, the eccentric joint moments during TRAD squatting are significantly smaller than concentric joint moments. It has however been demonstrated that eccentric joint moments can be enhanced with accentuated-eccentric loading. Therefore, the aim of this study was to investigate if training with accentuated-eccentric loading leads to greater strength & hypertrophy adaptations than TRAD.

Methods 22 strength trained males were split into a TRAD or 1 of 2 accentuated-eccentric loading groups (work matched or repetition matched). The TRAD group performed squats with 80% of 1RM during the concentric & eccentric phases. Both accentuated-eccentric groups performed squats with 80% during the concentric phase & 120% in the eccentric phase. All groups trained for 6 weeks with progressive overload each session. RPE & DOMS was collected throughout the intervention. Pre/post testing assessed; concentric, eccentric & isometric knee extensor joint moment (accompanied by vastus lateralis EMG), jump performance & squat 1RM. Vastus lateralis muscle architecture was assessed at the distal, mid-belly, & proximal site to identify muscle hypertrophy. A 2-way mixed ANOVA was used to assess the effects of the intervention & between groups differences.

Results There was a significant effect of training on knee extensor joint moments ($P < 0.001$), eccentric EMG ($P < 0.001$ to 0.043), & squat 1RM ($P < 0.001$). There was no effect of the intervention for any of the groups on improvements in jump height or concentric EMG ($P > 0.005$). Between group differences identified that only the AEL groups improved their ECC knee extensor joint moments. All groups improved their CON & isometric joint moments, with no difference between groups. Only the accentuated-eccentric loading groups displayed an increase in eccentric EMG, and reductions in ground contact time and increased reactive stretch index during a drop jump. At the start of the intervention, DOMS & RPE was significantly higher in the accentuated-eccentric loading groups than TRAD, however by session 8, no differences existed between groups. No differences were found between the work matched or repetition matched AEL groups for any outcome measure.

Conclusion This study has shown that accentuated-eccentric loading, but not TRAD, resulted in improvements in eccentric strength. These adaptations may be driven by neural mechanisms rather than changes in muscle architecture, at least in the short term. The perceived negative effects of accentuated-eccentric loading appear to be overcome after 4 weeks of training & thus we recommend that accentuated-eccentric loading should be prescribed in blocks exceeding this time frame. This training did not negatively impact on any other adaptations compared to TRAD, & therefore may be a valuable training method in sports that require high levels of eccentric force production such as changes of direction

6.2 Introduction

Resistance training has been highlighted as a powerful stimulus for improving the structure and function of skeletal muscle (Suchomel et al., 2018), and thus subsequent athletic performance (Suchomel et al., 2016). A vast body of literature has previously examined the effects of resistance training volume (Schoenfeld et al., 2017, Ralston et al., 2017), intensity (Schoenfeld et al., 2016) and frequency (Grgic et al., 2018), however, there is a dearth of research investigating the effects of modulating the loading during the different contraction phases of an exercise such as the squat (i.e., concentric (upwards) and eccentric (lowering) phases).

As was discussed in chapter two and demonstrated in chapter four, the greatest maximal forces can be measured during maximal-effort eccentric contractions, both in *ex-vivo* isolated muscle (Alcazar et al., 2019) and during whole body dynamic movements such as the squat (Armstrong et al., 2022b) However, following an investigation of squat kinetics, it was identified that eccentric forces during TRAD squatting were significantly below the concentric forces produced (see chapter five). Therefore, it could be suggested that the loading during the eccentric phase of TRAD may be sub-optimal, as it is limited by the load that can be lifted during the concentric phase, thus compromising the training adaptation and benefits.

One methodology of overcoming the limitations of TRAD is accentuated-eccentric loading (Suchomel et al., 2019a). In chapter five it was demonstrated that joint kinetics (peak joint moment & joint work) in the eccentric phase of squatting increase as accentuated-eccentric load increases, thus confirming that loading during TRAD may be sub-optimal. However, the literature is inconclusive concerning whether whole body dynamic accentuated-eccentric loading training is superior to TRAD training in terms of increasing muscular strength and performance.

Several investigations support the use of accentuated-eccentric loading as a superior training method (Douglas et al., 2018, Walker et al., 2016, Papadopoulos et al., 2014, Wirth et al., 2016, Cook et al., 2013, English et al., 2014, Harden et al., 2020b, Montalvo et al., 2021) to increase whole body, and single joint strength. However, other studies find no benefits of accentuated-eccentric loading above those of TRAD (Horwath et al., 2019, Toien et al., 2018, Yarrow et al., 2008, Fisher et al., 2016, Walker et al., 2020). This inconsistency was explored in detail in chapter two of this thesis, with the conclusion of that discussion suggesting that accentuated-eccentric loading may only be of benefit to strength-trained populations. Additionally, in chapter two it was identified that accentuated-eccentric loading may elicit eccentric-specific improvements in strength (Walker et al., 2016, Harden et al., 2020b), and may also improve markers of reactive strength (i.e., drop jump performance) (Papadopoulos et al., 2014), whilst also yielding similar improvements in concentric strength and muscle hypertrophy as TRAD resistance training (Roig et al., 2009).

Based on the aforementioned detail, it is evident that whole body dynamic accentuated-eccentric loading has potential as a specialised training modality, yet the existing evidence base is not definitive. One of the potential reasons why there are such conflicting results from accentuated-eccentric loading within the literature, is due to the varied loading schemes between studies, with accentuated-eccentric loads ranging from 106% to 125% of 1RM (Douglas et al., 2018, Montalvo et al., 2021, Walker et al., 2016, Cook et al., 2013). The data presented in chapter five of this thesis suggests that squatting with an accentuated-eccentric load of 120% of concentric 1RM may be optimal, as this is the load that maximised the eccentric peak joint moments and work, with a preferential loading of the knee extensors. Therefore, it may be necessary to train accentuated-eccentric loading with higher loads in order to see beneficial adaptations.

Despite the apparent benefits of accentuated-eccentric loading, many S&C coaches are cautious of incorporating this methodology within their practice (Harden et al., 2020a), given the increased potential for muscle soreness/damage, and RPE from performing resistance training with an eccentric focus (Hody et al., 2019, Paulsen et al., 2012). However, due to the repeated bout effect, ratings of DOMS can be decreased over time (Chen et al., 2019), although it is unclear how many bouts of accentuated-eccentric loading it would take to attenuate DOMS to the levels of TRAD DOMS.

As discussed in chapter five, there is a lack of scientific justification for how to program accentuated-eccentric loading, both in terms of loading and volume (Suchomel et al., 2019a, Harden et al., 2020a), Training volume has been shown to be a key modulator in resistance training adaptation (Ralston et al., 2017, Schoenfeld et al., 2019). In order to limit confounding variable when assessing the efficacy of manipulating training variable, it is important to minimise the effects of other training stimuli (e.g. different volume between intervention groups). However, there is debate over how to calculate resistance training volume. In chapter five it was demonstrated that during accentuated-eccentric loading, the amount of eccentric joint work performed during squatting is altered through the range of motion (Armstrong et al., 2022a). In order to control for the effects of volume, it was decided that two accentuated-eccentric loading groups will be utilised in this study [volume equalised for muscular work, and volume equalised by total number of repetitions] in comparison to TRAD.

It is evident from the literature that there are conflicting results from accentuated-eccentric loading training, with some studies supporting its use and others not. Therefore, the purpose of this study is to: A) compare the adaptations from TRAD and accentuated-eccentric loading resistance training in terms of; whole body muscular strength, single joint moment, and jump performance, in tandem with examinations of neural and architectural adaptations and B) to establish whether subjective measures of muscle soreness (DOMS) and perceived effort (RPE) are greater in accentuated-eccentric loading, and if these may be attenuated over time.

6.3 Methods

Participants: Twenty-two male participants were recruited for this study (23 ± 2 years, 83 ± 4 kg, 179 ± 4 cm). All participants had a history of resistance training (4 ± 2 years, 122 ± 21 kg squat 1RM) and could demonstrate correct squatting technique as determined by an experienced and accredited S&C coach. All participants gave written informed consent prior to the onset of the study in accordance with the declaration of Helsinki. This study was approved by the Liverpool John Moores University ethic committee (LJMU UREC: H21/SPS/069).

Experimental Design: Participants reported to the laboratories on eighteen occasions. Pre-testing and familiarisation sessions occurred during the first four visits (twice per week). Visits five to sixteen consisted of the experimental intervention sessions (twice per week), with the final two visits used for post-testing (see Table 6-1 for an overview).

Table 6-1 Overview of the experimental protocol, outlining the activities performed during each of the 18 sessions. T is indictive of a testing session, F is indictive of a familiarisation session.

Outcome Measure	Pre-Testing / Familiarisation				Training Intervention												Post-Testing	
	Week 1		Week 2		Week 3 to 8 (12 Training Sessions)												Week 9	
Session	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Muscle Architecture	T				*Participants allocated in to 1 of 3 training intervention groups.*												T	
Knee Extensor Moment / EMG	F	F	T		*TRAD – 4x6 (80% 1RM during Concentric phase, 80% 1RM during Eccentric phase)* *AEL4 - 4x6 (80% 1RM during Concentric phase, 120% 1RM during Eccentric phase)*												T	
Jump Performance				T	*AEL3 - 3x6 (80% 1RM during Concentric phase, 120% 1RM during Eccentric phase)*													T
Kineo & 1RM	F	F	F	T														T

Pre-testing and post-testing (described in detail below) assessed changes in strength through squat 1RM and concentric and eccentric knee extensor joint moment, combined with muscle activity, changes in architecture of the vastus lateralis muscle, and athletic performance in countermovement and drop jumps. The knee extensors, including vastus lateralis, were targeted for outcome measurement due to the data presented in chapter five showing that accentuated-eccentric loading preferentially loading the knee extensors during the eccentric phase of the squat (Armstrong et al., 2022a). During all pre-testing and post-testing sessions, participants were asked to refrain from strenuous physical activity for 72 hours. Throughout the training intervention, subjective measures of RPE (Zourdos et al., 2016) and DOMS were collected.

Familiarisation: Prior to study commencement, participants were familiarised with the testing and intervention equipment. All squatting was performed on the Kineo Training System (Kineo) which has been described in chapter three. In total, three familiarisation sessions were performed on the Kineo prior to the squat 1RM testing. Participants additionally completed a minimum of two familiarisation on an isokinetic dynamometer that was used for assessment of concentric, eccentric, and isometric knee extensor joint moment and muscle activity.

Training intervention: Participants were randomly allocated into either a control group or one of two experimental accentuated-eccentric loading groups, group characteristics are presented in table 6-2. The control group performed traditionally loaded resistance training (TRAD) which consisted of four sets of six repetitions of squats with the same load during the concentric and eccentric phases of the movement and initial load prescribed at 80% of 1RM (1RM identified during baseline testing). In the two experimental groups, the initial load was prescribed at 80% and 120% of 1RM during the concentric and eccentric phases, respectively. This eccentric load was chosen on the basis of the data presented in chapter five which identified that this eccentric load maximises lower limb joint kinetics during the eccentric phase of a squat (Armstrong et al., 2022a). The first experimental group (AEL4) performed the same number of repetitions as the control group (four sets of six repetitions), whilst the second experimental group (AEL3) was matched for total knee extensor work (Armstrong et al., 2022a) resulting in three sets of six repetitions.

Table 6-2 Participant baseline characteristics for the 3 interventional groups (TRAD n = 8, AEL4, n = 7, AEL3, n = 7)

	Body mass (kg)	Height (cm)	Squat 1RM (kg)	Isometric knee joint moment (N.kg)	Training Age (years)
TRAD	84.5 ± 3.8	177 ± 3	119 ± 19	324 ±72	4 ± 2
AEL4	82.9 ± 4.8	180 ± 4	123 ± 24	304 ± 86	5 ± 3
AEL3	83.4 ±5.4	179 ± 5	125 ± 25	388 ± 71	4 ± 3

Participants reported to the laboratory twice a week for six weeks (for a total of twelve training sessions). Prior to each training session, participants performed a dynamic warmup following the RAMP protocol (Jeffreys, 2006). For more details on this warmup, please refer to the appendices section. The warmup would finish with three sets of six repetitions at 20%, 40% and 60% of their squat 1RM on the Kineo. Participants would then perform their assigned training session, which was completed under the guidance of an experienced and accredited

S&C coach. Load was increased following each training session if all repetitions were completed, and that the participant reported an RPE of 9 or lower for the last set. Load progression for the TRAD group was in 2kg increments, whilst the AEL3 and AEL4 groups progressed their concentric load by 2kg and eccentric load by 3kg, thus enabling an equal ratio increase in the load compared to the initial load. RPE was collected ten minutes post completion of each training session (see section appendix section 9.2). Prior to the first training session and forty-eight hours post each training session, subjective rating of DOMS was collected via a 100 mm visual analogue scale (Cleather and Guthrie, 2007) (see appendix section 9.3).

Muscle architecture: B-Mode ultrasonography (38 mm probe, Epiq 7, Philips, Netherlands) was used to visualise fascicle length, pennation angle and thickness of the vastus lateralis in 2D-images at the distal, mid-belly and proximal sites of the vastus lateralis (Figure 6-1). Participants were asked to lay supine with the knee supported and flexed at 30° to minimise fascicle curvature at the distal site. Scanning sites were located according to those described by Blazevich *et al*., (2006), with small adjustments made to account for individual differences. The location of the scans was recorded relative to the anterior superior iliac spine and the superior boarder of the patella to facilitate measurement of the same location during post-intervention testing. Images were exported to ImageJ software (National Institute of Health, USA) for analysis of; muscle thickness, pennation angle and estimated fascicle length. Due to the full length of muscle fascicles being greater than the field of view, estimates of fascicle length were calculated (Ando et al., 2014). Muscle thickness was measured at three locations on each scan, with the mean result used for analysis. Pennation angle was determined by the angle at which fascicles attached to the lower aponeurosis, with up to three measurements being made per scan, and the mean result being used for analysis. Three individual scans of each location were performed, with the mean result being used for data analysis. The coefficient of variation (CV%) between the three repeated scans, which was used to indicate the practitioners' measurement reliability, was muscle thickness = 2.9% and pennation angle = 3.9%, respectively.

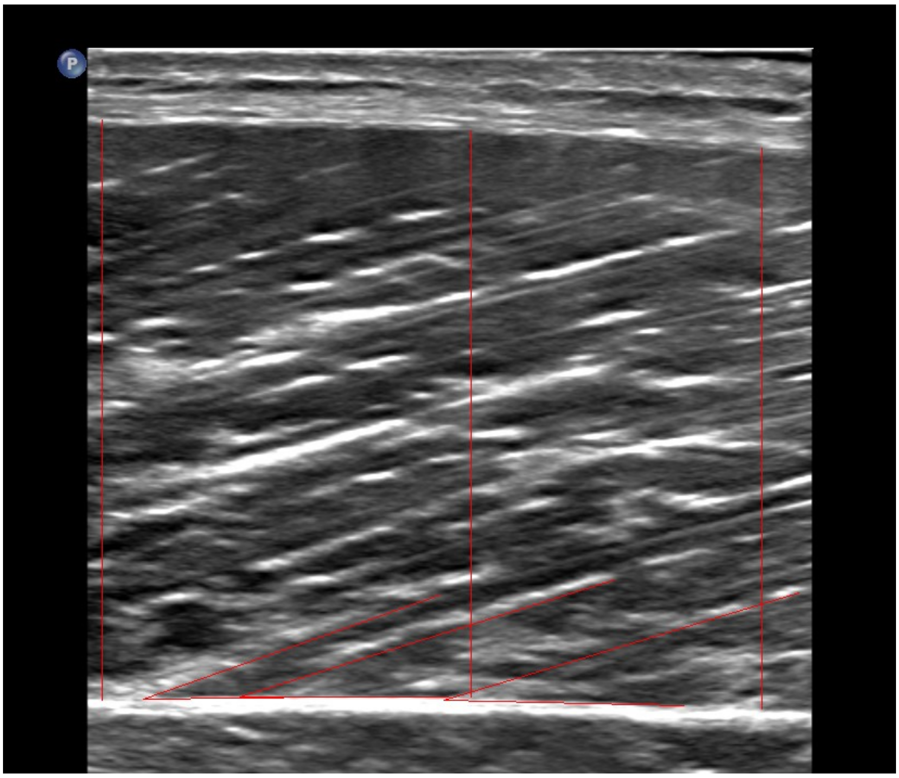

Figure 6-1 Example ultrasound image of the vastus lateralis with red overlay lines indicating where measures of muscle thickness and pennation angle were assessed

Knee extensor moment and activity: Isokinetic dynamometry (IKD) (HumacNorm, Computer Sports Medicine Inc., USA) was used to establish the joint moment-velocity relationship of the knee extensors using concentric, eccentric, and isometric maximum voluntary contractions of the dominant limb. Prior to testing, participants had been familiarised with the procedures on at least two occasions. Participants reported to the lab and were seated with the hip flexed at 85° and the centre of rotation of the knee (approximated as the lateral femoral condyle) aligned with the centre of rotation of the IKD during knee extension contraction. Participants completed a warmup which involved ten repetitions of knee extensor and flexor muscle actions on the IKD at 60 $°\cdot s^{-1}$, participants were instructed to increase the joint moment they produced each repetition with the 8th, 9th, and 10th repetition being performed at 80% of their perceived maximum effort. For the assessment of knee extensor moments, participants performed three repetitions at each joint velocity in a randomised order (isometric, concentric: 60 $°\cdot s^{-1}$, 180 $°\cdot s^{-1}$, 300 $°\cdot s^{-1}$, eccentric: -60 $°\cdot s^{-1}$, -180 $°\cdot s^{-1}$, -300 $°\cdot s^{-1}$). The joint angle for the isometric assessment was determined as the joint angle at which peak joint moment occurred at during the 60 $°\cdot s^{-1}$ trial, which approximates the optimum joint angle and accounts for the force-length relationship (Stotz et al., 2022).

During all trials, verbal encouragement and visual feedback was provided, with three to five minutes passive rest given between trials of each velocity and 30 seconds rest between repetitions within trials. All eccentric repetitions were preceded by a maximal concentric effort to ensure sufficient preload, which is required in order to maximise eccentric moment (Hahn, 2018). Joint moments, angle and velocity were captured by a BioPac MP150 (sampling at 1500 Hz) and recorded in AcqKnowledge (5.0.2, Biopac systems inc., USA) software. Recorded moments were gravity corrected to account for the weight of the lower leg and dynamometer arm (Nelson and Duncan, 1983). The peak joint moment from each trial was used for subsequent analysis.

Electromyographic (EMG) activity of the vastus lateralis was recorded synchronously with moments during all trials. The skin was prepared by shaving excess hair, abrading to remove dead skins cells, followed by an alcohol swab to remove any oils. Electrodes (Ambu Blue, Denmark) were placed on the vastus lateralis in accordance with SENIAM guidelines (Hermens et al., 1999) and were connected to a BioNomadix wireless transmitter (Biopac systems inc., USA). EMG signals were band-pass filtered (10-250 Hz) and root-mean-squared (100 ms). All signals were then normalised to the peak isometric EMG as a reference. The EMG value that occurred during the peak joint moment for each trial was used for final analysis.

One-repetition maximum and jump performance: Prior to assessment, participants underwent the RAMP based warmup. Participants then performed three repetitions of three jump variations; squat jump, countermovement jump, and drop jump on a force plate (9287c, Kistler, Switzerland) sampling at 1000 Hz in AcqKnowledge software. All jumps were performed with the hands placed on the hips in order to minimise any effects from an arm swing (Lees et al., 2004). During the squat jump, participants were asked to squat down until the knee was flexed to 90°, pause for three seconds and then perform a maximal vertical jump. During the countermovement jump, participants began standing with knees and hips extended, before rapidly squatting down until the knee was flexed to 90° before performing a maximal vertical jump. During the drop jump, participants began by standing on a 60 cm box, this height was selected in order to maximise the eccentric braking forces required (Makaruk and Sacewicz, 2011), whilst being able to maintain a short ground contact time (Addie et al., 2019). Participants would then step off the box landing with both feet onto the force plat before performing a maximal vertical jump. Participants were instructed to minimise ground contact time during the maximal vertical jump. Jump height of the three jumps variations were calculated from the take-off velocity utilising the equation of constant acceleration (Moir, 2008). Three repetitions of each jump variation were performed with 30 seconds passive rest between repetitions, and three to five minutes passive rest between jump variations, with peak values utilised for analysis.

Following the jump assessments, participants then performed the 1RM assessment following guidelines from the National Strength and Conditioning Association (Haff and Triplett, 2015). In brief, participants performed several progressively heavier warm up squats on the Kineo, adhering to the technique outlined in the familiarisation, until they reached a load of 90% of their estimated 1RM. Participants were then given five attempts to achieve a 1RM, with the heaviest load performed with correct technique being recorded. Following the completion of the 1RM, the participant was asked to identify their RPE on a scale of 1-10, with these ratings anchored against perceived number of repetitions in reserve, which has been shown to accurately reflect exertion in the squat in strength-trained males (Zourdos et al., 2016).

Statistical analyses: All data were checked for normality, and homogeneity of variance using a Shapiro-Wilk and Levene's tests, respectively. In order to test the primary aim, a two-way (3x2) mixed analysis of variation (ANOVA), with 3 between subject factors and 2 within subject factors, was used to identify if there was a significant main effect between pre- and post-testing, and if there was an interaction between the experimental group allocation and the pre-test to post-test difference. Two polynomial-quadratic contrast comparisons were used to identify whether a) differences existed between the pre-test post-test difference between the control (TRAD) and experimental groups (AEL4 and AEL3), and b) whether differences existed between the two experimental groups (AEL4 and AEL3) for each outcome measure. Contrast effect sizes were calculating using r with 0.2, 0.5, and 0.8 representing a small, medium and large effect size (Field, 2013). In order to test the second aim (RPE and DOMS), a two-way (3x12) mixed ANOVA with 3 between subject factors and 12 within subject factors, was used to identify if there was a main effect and interaction. A Bonferroni post-hoc was used to identify at which session RPE and DOMS were no longer significantly different from each other, and a between groups ANOVA with Welch F-ratio adjustment was used to compare the difference in DOMS and RPE at each time point. For all data, values are reported as mean ± standard deviation, with a statistical significance set to an alpha of 0.05. All analyses were performed in Statistical Package for the Social Sciences (SPSS version 27, IBM, USA).

6.4 Results

Changes in muscular strength and electromyographic activity: Squat 1RM increased significantly in all three groups during the training intervention ($F = 153.959$, $P < 0.001$) (Figure 6-2), with a significant interaction between the training intervention and groups on improvements in 1RM (*F*= 3.975, *P* = 0.036). Planned contrasts identified that both accentuated-eccentric loading experimental groups had greater improvement in squat 1RM (AEL4: 15 ± 7 kg, AEL3: 14 ± 6 kg) than the TRAD group (9 ± 5 kg) ($t = 3.04$, $P = 0.07$, $r = 0.54$). However, there was no difference in improvements between the AEL4 and AEL3 groups ($P = 0.753$).

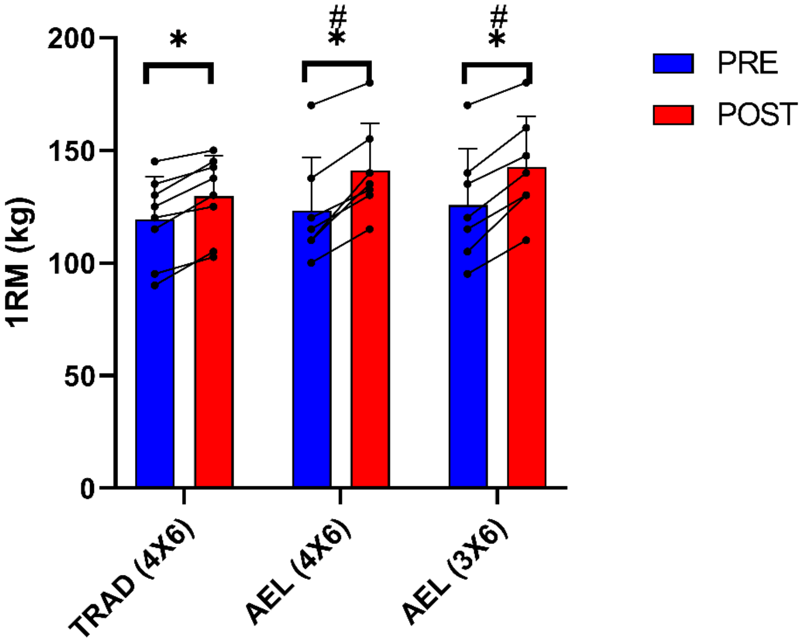

*Figure 6-2 Mean (± SD) Kineo squat one-repetition maximum (kg), for the control and two experimental groups. * indicates a signifficant difference (P < 0.05) from pre to post-testing. # indicates post-test difference was significantly different (P < 0.05) from the control group (TRAD n = 8, AEL4 n = 7, AEL3 n = 7).*

Likewise, concentric and isometric knee extensor moments increased for all three groups during the training intervention (Figure 6-3, Figure 6-4, & Figure 6-5) by 6.4 ± 0.6% ($F = 15.792$, $P < 0.001$), 12.3 ± 3% ($F = 59.676$, $P < 0.001$), 12.5 ±2.7% ($F = 23.848$, $P < 0.001$), and 13.6 ± 1.6% ($F= 15.475$, $P < 0.001$) for the isometric, 60 $°\cdot s^{-1}$, 180 $°\cdot s^{-1}$, and 300 $°\cdot s^{-1}$ trials respectively, with no significant interaction between groups ($P = 0.467$ to 0.787).

There was a significant main effect of the training intervention on eccentric knee extensor moment for the -60 °·s^{-1} ($F = 25.711$, $P < 0.001$), -180 °·s^{-1} $F = 22.777$, $P < 0.001$), and -300 °·s^{-1} ($F = 21.914$, $P < 0.001$) trials, with a significant interaction of the training intervention between groups on improvements in eccentric knee extensor moment ($F = 7.738$, $P = 0.003$, $F = 3.588$, $P = 0.048$, $F = 4.791$, $P = 0.025$). However, planned contrasts identified that only the accentuated-eccentric loading groups experienced a significant increase in eccentric knee extensor moments following the intervention (AEL4: 16.2%, 8.1% and 9.7%, AEL3: 16.2%, 12.5%, and 10%) ($t = 4.076$, $P < 0.001$, $r = 0.657$, $t = 2.392$, $P = 0.027$, $r = 0.432$, $t = 2.979$, $P = 0.010$, $r = 0.558$). No significant difference was identified between the AEL4 and AEL3 groups ($P = 0.369$ to 0.790).

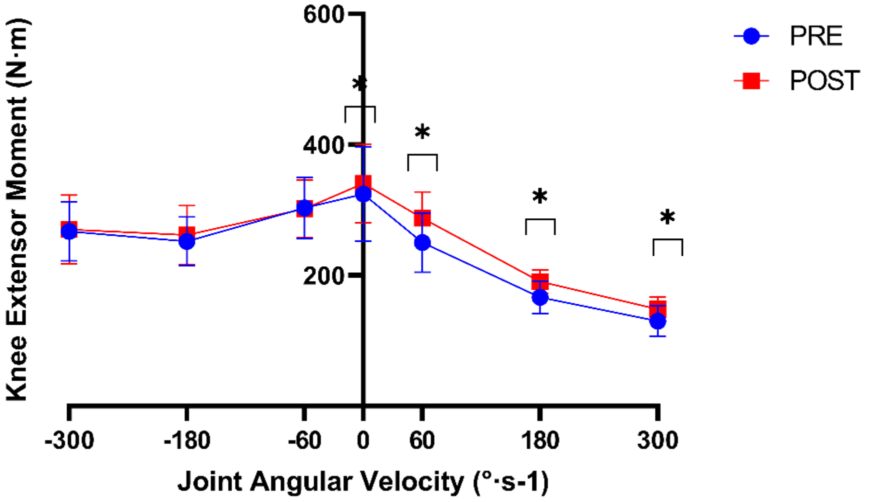

*Figure 6-3 Knee extensor joint moment-velocity relationship for the TRAD group. * Indicates significant difference (P < 0.05) from pre- to post-testing (n = 8)*

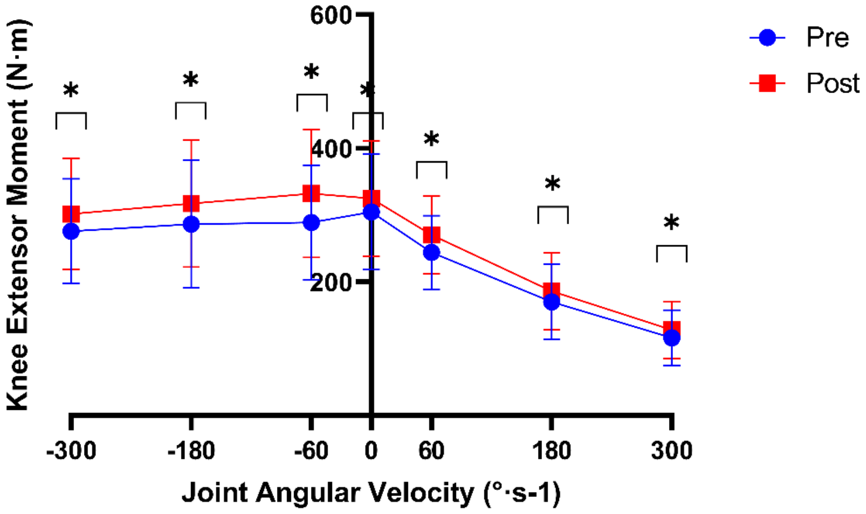

*Figure 6-4 Knee extensor joint moment-velocity relationship for the AEL4 group. * Indicates significant difference (P < 0.05) from pre- to post-testing (n = 7)*

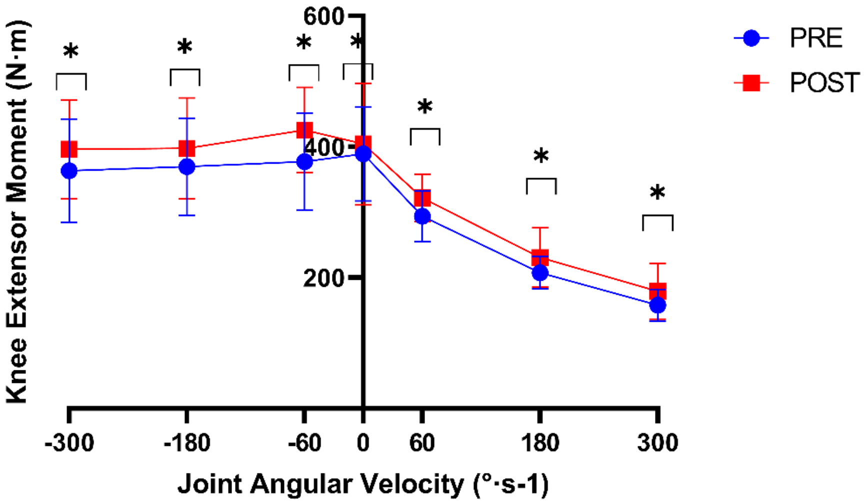

*Figure 6-5 Knee extensor joint moment-velocity relationship for the AEL3 group. * Indicates significant difference (P < 0.05) from pre- to post-testing (n = 7)*

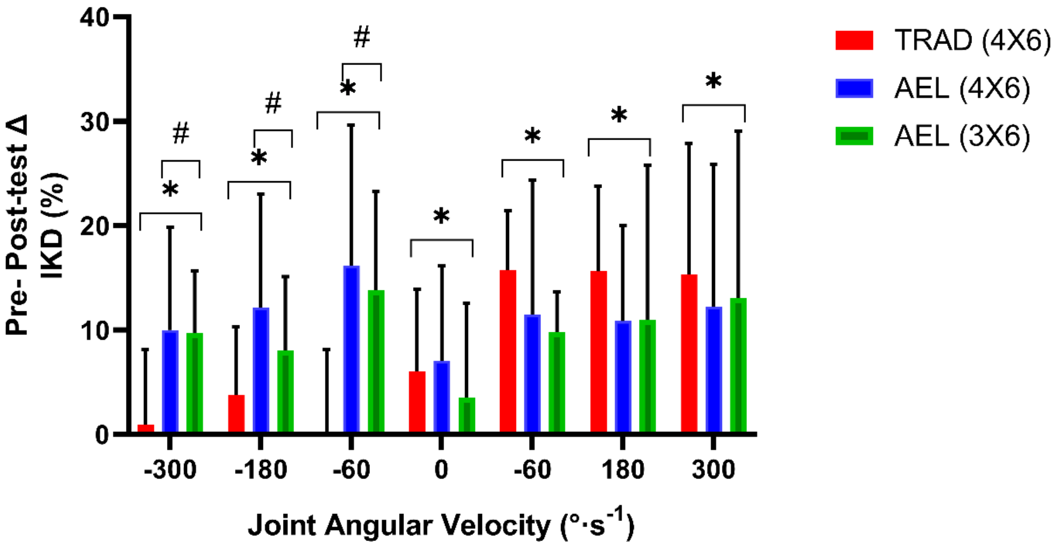

*Figure 6-6 Mean (± SD) pre- post-test change (%) in concentric, isometric, and eccentric Knee extension joint moment. * indicates a significant difference (P < 0.05) from pre to post-testing. # indicates post-test difference was significantly different from the control group (TRAD n = 8, AEL4 n = 7, AEL3 n = 7).*

There was no main effect of the training intervention on the electromyographic activity during the isometric trial ($F = 0.146$, $P = 0.865$) indicating that the isometric EMG is stable between assessments, and therefore normalised EMG was analysed to control for individual differences between participants in EMG magnitude. There was no main effect of the training intervention on the concentric normalised electromyographic activity ($P = 0.128$ to 0.837). However, there was a main effect of the training intervention on the assessment of eccentric knee joint moments for the -60 $°\cdot s^{-1}$ ($F = 24.459$, $P < 0.001$), -180 $°\cdot s^{-1}$ ($F = 13.624$, $P = 0.002$), and -300 $°\cdot s^{-1}$ trials $F = 4.707$, $P = 0.043$), with a significant interaction on normalised EMG activity ($F= 8.337$, $P = 0.003$, $F = 4.298$, $P = 0.029$, $F = 4.543$, $P = 0.024$). Planned contrasts identified that the accentuated-eccentric loading groups, but not the TRAD group, had an increase in normalised eccentric EMG ($t = 3.793$, $P = 0.003$, $r = 0.68$, $t = 2.781$, $P = 0.017$, $r = 0.55$, $t = 2.988$, $P = 0.009$, $r = 0.56$). No differences were found between the two accentuating-eccentric loading groups ($P = 0.533$ to 0.701), with normalised eccentric EMG activity increasing from 0.71 (± 0.07) to 0.82 (± 0.08), 0.67 (± 0.07) to 0.78 (± 0.07), and 0.66 (± 0.08) to 0.74 (± 0.07) for the -60 $°\cdot s^{-1}$, -180 $°\cdot s^{-1}$, and -300 $°\cdot s^{-1}$ trials, respectively (Figure 6-7).

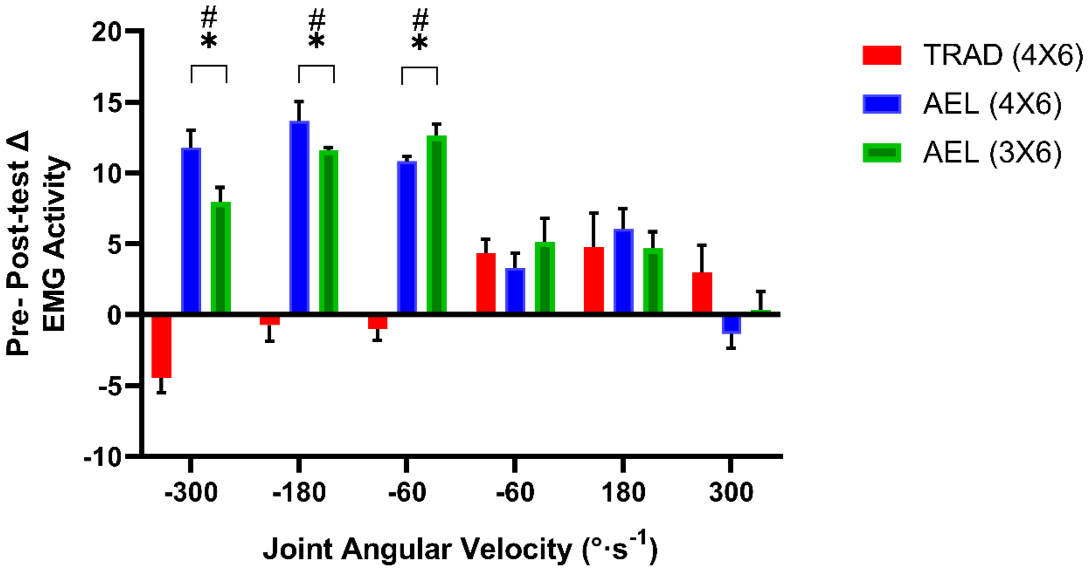

*Figure 6-7 Mean (± SD) change (%) in normalised electromyographic activity of the vastus lateralis during maximal concentric and eccentric knee extensions. * indicates a signifficant difference (P < 0.05) from pre to post-testing. # indicates post-test difference (P < 0.05) was significantly different from the control group (TRAD n = 8, AEL4 n = 7, AEL3 n = 7).*

Changes in muscle architecture: There was no main effect of the training intervention on measurements of pennation angle or estimates of fascicle length at either the distal, mid-belly or proximal sites for either of the three intervention groups (*P* = 0.074 to 0.758), nor was there a main effect on muscle thickness at the distal site (*F* = 0.3868, *P* = 0.650). However, there was a main effect of the training intervention on muscle thickness at the mid-belly site (*F* = 5.559, *P* = 0.030) and the proximal site (*F* = 7.215, *P* = 0.015). There was no interaction between groups on measures of muscle thickness for either the mid-belly (*F* = 0.325, *P* = 0.727) or the proximal site (*F* = 1.297, *P* = 0.298), with planed contrasts finding no significant differences between groups (*P* = 0.539 to 0.939) (see Table 6-3).

*Table 6-3 Mean (± SD) muscle architecture of the vastus lateralis at the distal, mid-belly, and proximal site locations. * indicates a significant difference (*$P < 0.05$*) from pre to post-testing (TRAD n = 8, AEL4 n = 7, AEL3 n = 7)..*

		Distal		Mid-Belly		Proximal	
		Pre	Post	Pre	Post	Pre	Post
Muscle Thickness (mm)	TRAD	23.2 ± 3.5	24.1 ± 5.0	25.3 ± 3.5	26.3 ± 4.5*	26.3 ± 3.8	26.4 ± 4.3*
	AEL4	24.7 ± 2.5	25.1 ± 2.1	27.7 ± 2.7	28.2 ± 2.1*	26.1 ± 2.2	26.7 ± 2.0*
	AEL3	22.5 ± 2.0	23.5 ± 1.9	26.9 ± 2.7	27.4 ± 3.1*	25.9 ± 3.4	26.6 ± 3.7*
Pennation Angle (°)	TRAD	17.2 ± 5.4	17.4 ± 3.8	16.4 ± 2.9	16.8 ± 2.9	16.6 ± 2.5	16.9 ± 2.2
	AEL4	17.4 ± 2.1	17.3 ± 2.5	17.1 ± 1.0	16.7 ± 0.8	16.7 ± 1.3	16.7 ± 1.5
	AEL3	16.0 ± 1.3	16.8 ± 2.5	16.8 ± 2.5	16.9 ± 1.7	15.9 ± 1.2	16.1 ± 0.9
Fascicle Length (mm)	TRAD	83.1 ± 21.1	81.3 ± 14.2	90.8 ± 14.7	92.0 ± 14.4	90.4 ± 8.1	87.3 ± 9.9
	AEL4	83.2 ± 7.9	85.5 ± 10.2	94.4 ± 12.4	98.1 ± 9.9	92.2 ± 8.3	93.9 ± 11.4
	AEL3	81.7 ± 9.1	81.2 ± 3.6	93.6 ± 7.9	94.1 ± 8.6	97.5 ± 13.8	95.9 ± 10.3

Changes in jump performance: No main effect of the training intervention was found on changes in the height of the countermovement jump, squat jump, or drop jump ($P = 0.112$ to 0.995) However, there was a main effect of the training intervention on drop jump characteristics with a reduction in ground contact time ($F = 4.593$, $P = 0.046$) and an increase in reactive strength index ($F = 4.341$, $P = 0.05$)). There was a significant interaction between the training intervention and groups on the changes in ground contact time ($F = 4.916$, $P = 0.020$), and reactive strength index ($F = 5.425$, $P = 0.14$). Planned contrasts identified ground contact time decreased in the accentuated-eccentric loading groups (-8.2%), whilst the TRAD group increased ground contact time (+6.1%)($t = 4.596$, $P < 0.001$, $r = 0.68$)). Planned contrasts also revealed an improvement in reactive strength index for the accentuated-eccentric loading groups, but not the TRAD group ($t = 2.816$, $P = 0.014$, $r = 0.65$). Planned contrasts found no difference between the two accentuated-eccentric groups for either ground contact time ($P = 0.95$) or reactive strength index ($P = 0.091$)

Changes in subjective RPE and DOMS: There was a main effect of the training intervention on the subjective RPE score (*F* = 10.961, *P* < 0.001) and a significant interaction between the training intervention and groups on the RPE score (*F* = 1.582¸ *P* = 0.05) (Figure 6-8). Bonferroni post-hoc found no significant changes in RPE after session 8. After the first session there was a significant difference between the three groups (*F*= 6.118, *P* = 0.015). Both accentuated-eccentric loading groups had a significantly greater RPE (8.6 ± 0.4) than the TRAD group (7.7 ± 0.5) (*t*= 3.417 *P* = 0.005, *r* =0.633), with no differences between accentuated-eccentric loading groups (*t*= -0.264, *P* = 0.797). However, after the eighth session there was no significant difference between the three groups (RPE = ~7.7) (*F*= 593, *P* = 0.120).

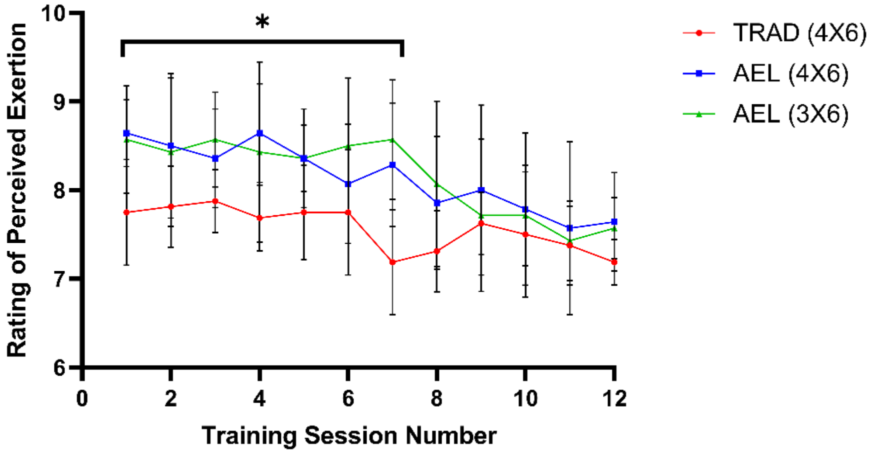

*Figure 6-8 Mean (± SD) rating of perceived exertion taken after the completion of each of the 12 training sessions. * indicates a significant difference (P < 0.05) between AEL and TRAD (TRAD n = 8, AEL4 n = 7, AEL3 n = 7).*

There was a main effect of the training intervention on the subjective measure of DOMS (*F* = 10.764, *P* < 0.001) and a significant interaction between the training intervention and groups on the DOMS score (*F* = 10.764, *P* < 0.001) Bonferroni post-hoc found no significant changes in DOMS after session 8. In the TRAD group, DOMS remain constant throughout the intervention (41 ± 2) (*F*= 1.050, *P* = 0.413), however, rating of DOMS decreased throughout the intervention for the AEL4 group (*F*= 7.525, *P* < 0.001) and the AEL3 group (*F*= 5.101, *P*

<0.001) (Figure 6-9). Forty-eight hours post intervention session one, there was a significant difference between groups (*F*= 46.768, *P* < 0.001,). Both accentuated-eccentric loading groups had significantly greater DOMS than the TRAD group (*t*= 9.759, *P* < 0.001, *r* = 0.878), with no differences between accentuated-eccentric loading groups (, *P* = 0.78). However, 48 hours post intervention session eight there was no significant difference in DOM between the three groups (*F*= 2.490, *P* = 0.125).

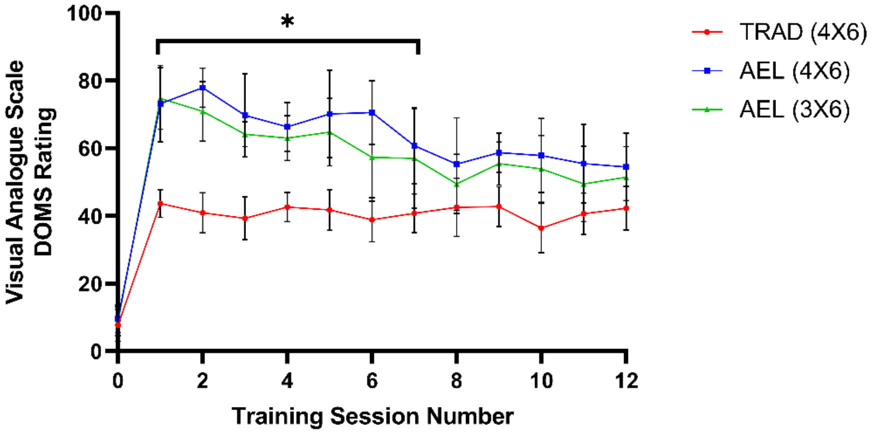

*Figure 6-9 Mean (± SD) rating of delayed onset of muscle soreness collected prior to the first training session (0), and 48 hours after the completion of each of the 12 training sessions. * indicates a significant difference (P < 0.05) between AEL and TRAD (TRAD n = 8, AEL4 n = 7, AEL3 n = 7).*

6.5 Discussion

The purpose of this study was to investigate whether accentuated-eccentric loading resulted in different adaptations when compared to traditional loading paradigms in the squat exercise. The primary finding of this study was that both accentuated-eccentric loading squatting groups demonstrated greater improvements in 1RM and eccentric knee extensor strength than the TRAD squatting group. Additionally, the accentuated-eccentric loading groups also displayed greater improvements in reactive strength in drop jumping, and an increased eccentric neural activity during eccentric actions. It was also found that detrimental effects of accentuated-eccentric loading (higher levels of DOMS and RPE) are attenuated after completing eight training sessions, resulting in similar DOMS and RPE to those seen during TRAD squat loading, without any detected negative effects on performance outcomes at intervention completion. Finally, there was no apparent difference between performing accentuated-eccentric loading with either three (work matched) or four sets (repetition matched), therefore all subsequent discussion will consider accentuated-eccentric loading findings collectively.

One of the primary outcome measures of this study was the assessment of changes in Kineo squat 1RM. All three groups significantly increased their 1RM, however the accentuated-eccentric loading groups had a significantly greater increase than the TRAD group (Figure 6-2), which is in agreement with previous literature (English et al., 2014, Douglas et al., 2018, Cook et al., 2013). This is of particular interest as successful completion of a squat 1RM is dictated by the ability to generate forces during the concentric phase of the squat (Swinton et al., 2012). However, in the present study, concentric load was the same for all groups, and therefore the greater loading from accentuated-eccentric loading likely had a transference effect to concentric adaptations. Potentially by providing additional training stimuli to the quadriceps muscle in the lengthened position (as demonstrated in chapter five), which is critical for squat performance (Choe et al., 2021).

This study also examined muscular strength under a variety of conditions and demonstrated that training with accentuated-eccentric loading, but not TRAD, resulted in improvements in eccentric knee extensor joint moments across a range of velocities (-60 $°\cdot s^{-1}$ to -300 $°\cdot s^{-1}$), even though squatting with accentuated-eccentric loading typical occurs at much lower velocities (average -53 to -79 $°\cdot s^{-1}$), as demonstrated in chapter five. This therefore suggests that eccentric strength adaptations may not be specific to the velocity at which they are trained, which is contrary to what has been shown previously in single-joint modalities (Paddon-Jones et al., 2001).

Previous literature has shown that only fast eccentric actions resulted in improvements in high velocity eccentric strength (Paddon-Jones et al., 2001) with changes in muscle architecture being the often cited cause of these adaptations (Sharifnezhad et al., 2014). However, the data presented in this chapter demonstrated only small changes in muscle thickness, which were not different between groups and in line with typical resistance training adaptations for this time frame (Baz-Valle et al., 2019) and no changes in pennation angle or fascicle length (see Table 6-3). This may have been due to the short nature of this study, with more significant architectural changes usually requiring a longer time frame (Blazevich et al., 2007). Rather the findings of this chapter suggest that the increase in both slow and fast eccentric strength that only occurred on the accentuated-eccentric loading groups may be due to the ~12% increase in vastus lateralis neural activity across all eccentric velocities assessed (at least in the short term). It has been previously suggested that the neural activity strategy during eccentric muscular contraction differs to that during concentric muscular contractions (Duchateau and Enoka, 2016). which is demonstrated by a decreased voluntary activation (Beltman et al., 2004) and cortical and spinal excitability (Duclay et al., 2014) during eccentric contractions. However, chronic eccentric resistance training may overcome these limitations (Hedayatpour and Falla, 2015), thus explaining why improvements were only observed in eccentric strength and neural activity in the accentuated-eccentric loading groups, whilst the TRAD group saw no changes in eccentric neural activity. Therefore, if high levels of eccentric strength are required for sporting performance, particularly if the velocities at which these forces occur at are highly variable, it may therefore be beneficial to include accentuated-eccentric loading within a S&C programme.

The data from the present study on single-joint concentric and isometric strength are in agreement with the previous literature (Horwath et al., 2019, Douglas et al., 2018, Walker et al., 2016, Cook et al., 2013, English et al., 2014, Harden et al., 2020b, Montalvo et al., 2021), whereby both TRAD and accentuated-eccentric loading resulted in similar improvements in concentric and isometric strength.. The similar increases in concentric strength may be due to the same magnitude of loading during the concentric phase of both the TRAD group and accentuated-eccentric loading groups (80% of 1RM). Therefore, this may suggest that training with accentuated-eccentric loading specifically to elicit eccentric specific adaptations do not limit concentric and isometric adaptations.

The data presented in this chapter identified no changes in the heights achieved for either squat jumps, countermovement jumps, nor drop jumps following either TRAD or accentuated-eccentric loading, which is consistent with previous literature (Douglas et al., 2018). It has been suggested that in strength-trained populations, resistance training alone is not sufficient to elicit a change in jump performance (Baker, 1996), rather high-velocity concentric efforts that utilise a fast stretch-shortening cycle are required. Therefore, the results are unsurprising as the participants in the present study were classified as strength-trained. Additionally, the data collected in chapter five indicates that the concentric velocity during squats at 80% of 1RM is ~0.5 $m \cdot s^{-1}$ (Armstrong et al., 2022a), whereas the velocities achieved during jumping is typically in excess of 2.5 $m \cdot s^{-1}$, which could explain why there was no transference in increased strength to jumping performance. To achieve these high velocities and improve jump performance, it has been suggested that during accentuated-eccentric loading, concentric loading should be in the region of 30% 1RM (Merrigan et al., 2022). Future research may wish to examine if a combination of high load accentuated-eccentric loading combined with jump specific training leads to greater transference when compared to TRAD and jump specific training.

Although there were no changes in jump height, the accentuated-eccentric loading groups reduced their ground contact time by ~8% time during the drop jump, thus improving reactive strength, which is similar to what has been reported previously (Douglas et al., 2018, Papadopoulos et al., 2014, Horwath et al., 2019). It has been suggested that this may be due to a modulated neural activity, with Komsis *et al*., (2014) finding higher level of pre-activation in the gastrocnemius during drop jumps following eccentric resistance training. Tendon stiffness has also been shown to correlate with ground contact time during drop jumps (Abdelsattar et al., 2018), however Walker *et al*., (2020) suggests that accentuated-eccentric loading does not influence tendon properties, at least in the short term. Combined with observation of no changes in muscle architecture, it seems plausible that the decrease in ground contact time found in the present study might be due to the ability to better tolerate high eccentric forces and changes in neural activity. Taken together it appears that the neural adaptations from accentuated-eccentric loading squatting are both transferable to slow and fast maximal eccentric muscle contractions, as well as reactive sporting movements.

As expected, the self-reported DOMS during the initial training sessions was greater in the accentuated-eccentric loading groups than in the TRAD group. It has been well established that eccentric training can result in more muscle damage than TRAD training (Paulsen et al., 2012) and subsequent DOMS (Hody et al., 2019). However, the severity of DOMS and muscle damage can be reduced by repeated exposure to eccentric resistance training i.e., the repeated bout effect (Chen et al., 2019). In the present study, ratings of DOMS decreased after each subsequent bout of accentuated-eccentric loading, until the completion of session eight, whereby DOMS rating was equivalent to those experienced during TRAD. Similar finding was found for rating of perceived exertion. This therefore suggests that the perceived negative effects of accentuated-eccentric loading can be attenuated with sufficient exposure. Future research may wish to investigate how long this repeated bout effect last after cessation of accentuated-eccentric loading.

6.6 Conclusion

This study has demonstrated that strength-trained males utilising accentuated-eccentric loading achieved superior improvements in Kineo squat 1RM, eccentric knee extensor strength, reactive strength index, and drop jump ground contact time compared to TRAD, whilst also achieving similar improvements in concentric and isometric knee extensor strength. Changes in eccentric specific strength were likely due to neural adaptations in the short term. Therefore, accentuated-eccentric loading may be a useful training modality for sports that require high levels of eccentric force production and reactive strength, such as those with high rates of change of direction (Jones et al., 2017) or to better condition the skeletal muscle to handle to the large eccentric forces during landings in sports (McAlpine et al., 2012, Cossin et al., 2021). It was also demonstrated that the increased muscle soreness and perceived effort associated with eccentric training is reduced following eight sessions, and therefore the inclusion of accentuated-eccentric loading needs to be carefully considered within the long-term periodised training programme. As no differences were found between performing accentuated-eccentric loading with three or four sets, future research may wish to identify minimum and maximum effective training volumes for squat based accentuated-eccentric loading, as well as examining the effects of accentuated-eccentric loading combined with plyometric training to see if there is a potentiation of explosive concentric performance.

Chapter 7.

Synthesis of Findings

The novel data presented within this thesis will help to significantly develop several fields of research relating to lower body multi-joint eccentric resistance training, as well as improving applied S&C practice for the implementation of accentuated-eccentric loading of the squat exercise. The following chapter summarises the key findings of this thesis, with particular reference to the aims laid out in chapter one. This chapter will include a general discussion of the findings, the practical implications of how accentuated-eccentric loading may be utilised within applied practice, the limitations of the studies that were undertaken, and finally recommendations of how future research may build upon the work presented within this thesis.

7.1 Achievement of Aims

The overarching aim of this thesis was to improve the understanding of the underpinning movement dynamics during accentuated-eccentric loading, and to identify if this could be a viable resistance training methodology in strength-trained populations. To achieve this aim, a training intervention would need to be devised that would compare the adaptations from traditional resistance training to accentuated-eccentric loading resistance training. However, due to the limited knowledge of how to programme this method of training, it was first paramount to understand what effect different eccentric loads had on squat kinetics, kinematics, and muscle activity, as well as understanding what the maximum capabilities of force production where during eccentric squatting. In the following sections, each of the specific aims mentioned within chapter one will be evaluated.

7.1.1 Assessment of the Capabilities of the Kineo Training System for Squatting and Eccentric Loading

Although the primary aim of this thesis was to investigate eccentric movement dynamics and subsequent adaptations in the squat exercise, it was first necessary to ensure that the equipment that was to be used to facilitate the eccentric loading was fit for the purpose of this thesis. This topic was addressed in chapter three, as no previous published body of work had been produced on the Kineo Training System. The data in chapter three was split in to two primary research questions a) are squats performed on the Kineo replicable of squats performed on the barbell. And b) is the Kineo valid and reliable for facilitating eccentric isovelocities in order to assess maximal eccentric force production.

As demonstrated in chapter three section 3.2, the kinematics produced during squats performed on the Kineo are similar to those performed on the barbell, as are the electromyographic measures of muscle activity, with the Kineo squat tending to be more replicable of a barbell front squat rather than that of a barbell back squat. However, these differences were minor. This is the first time the kinematics and muscle activity of squats performed on the Kineo have been investigated. In section 3.3, the validity and reliability of the isovelocity mode of the Kineo was assessed during the eccentric (-0.75 $m{\cdot}s^{-1}$, -0.5 $m{\cdot}s^{-1}$, -0.25 $m{\cdot}s^{-1}$) and concentric phase (0.75 $m{\cdot}s^{-1}$, 0.5 $m{\cdot}s^{-1}$, 0.25 $m{\cdot}s^{-1}$) of the squat. Only small coefficients of variation were identified for change in measured velocity from repetition to repetition, whilst Bland-Altman analyses identified a small bias from the prescribed velocity of ~0.01 $m{\cdot}s^{-1}$. Taken together, these results indicated that the Kineo was valid and reliable, and would be fit for the purpose of facilitating eccentric squatting.

7.1.2 Determining Concentric and Eccentric Force-Velocity Profiles During Squatting

The first primary objective of this thesis was to establish the force-velocity relationship during squatting. This was important to understand as it was unknown to what magnitude maximal eccentric force were capable of being produced during squatting. As discussed in chapter four, no previous published work has examined both the maximal forces capable of being produced during the eccentric and concentric phases of a squat across a range of velocities. The data that was presented in chapter four section 4.3, confirmed that maximal eccentric force production in a squat is in agreement with the previous literature on single-joint movements, and conforms to the typical in-vivo profile. However, the magnitude of increase in eccentric force above the isometric force (1.1 times) is smaller than what is typically seen in single-joint assessments (Alcazar et al., 2019). Furthermore, as demonstrated in section 4.3.1, variability exists between participants in the ability to generate maximum eccentric forces during squatting, and this is independent of the participant concentric ability. These data highlight the fact that just because and individual may have a well-developed concentric ability, does not mean that they are capable of producing high eccentric outputs, signifying that eccentric specific training may be required.

7.1.3 Determining Movement Dynamics and Muscle Activity During the Eccentric Phase of Squatting with Traditional and Accentuated-Eccentric Loading

The second aim of this thesis was to explore the movement dynamics of the eccentric phase of the squat, as the majority of previously published literature focused on the concentric phase (as discussed in chapter two). Understanding these movement dynamics were critical in order to design the accentuated-eccentric loading resistance training programme, as it was unknown what eccentric load would maximise the potential stimulus for adaptation. This aim was achieved by a) examining kinematics presented during squatting. And b) by assessing the peak joint moments and joint work for the hip, knee and ankle extensors during both the concentric and eccentric phase of the squat under both traditional loading paradigms (20 to 100% of 1RM), and under accentuated-eccentric loading paradigms (100 to 150% of 1RM). This data was presented in chapter five and is the first investigations of squat movement dynamics under both traditional and accentuated-eccentric loading. Exploration of this data revealed several novel and important findings. Firstly, joint moments were always greater in the concentric phase than in the eccentric phase, despite the capability to produce greater forces in the eccentric phase of a squat (as identified in chapter four). This is likely due to the acceleration effects of gravity assisting in the eccentric phase, and having to be overcome in the concentric phase. Secondly, and of more interest, it was demonstrated that only the knee extensors experienced a significant increase in peak joint moments when accentuated-eccentric loading was incorporated, thereby suggesting that accentuated-eccentric loading preferentially loads the knee extensors. This increase in knee extensor moment plateaued at a load of 120% 1RM. Of interest, the increase in joint moment with accentuated-eccentric loading was independent of any increase in neural activity of the vastus lateralis, suggesting that mechanical rather than neural factors are the cause of this increased joint moment. The information gleaned from this study was invaluable in the construction of the training intervention that was discussed in chapter six.

7.1.4 Assessment of the Effectiveness of Accentuated-Eccentric Loading in Comparison to Traditional Loading in The Squat

The final aim of this thesis was to investigate if a training program that utilised accentuated-eccentric loading led to superior and/or eccentric specific adaptations compared to a traditional loading paradigm. To achieve this aim, the data that was discussed in chapters four and five was used to construct a 12-session long resistance training programme, this data also aided in the development of the outcome measures. Without the knowledge gained from chapters four and five, the loading schemes implemented in chapter six could not have been scientifically justified.

The results of this intervention were discussed in chapter six. Although several studies have previously compared accentuated-eccentric loading to traditional resistance training, this study was the first to examine maximum whole-body strength (1RM) and specific adaptations in strength across the range of concentric and eccentric moment-velocity profiles, whilst also considering neural and hypertrophic adaptations. In addition, this is the first study that has controlled for volume differences between traditional and accentuate-eccentric loading by accounting for total joint work (which was identified from the data in chapter five).

The data presented in chapter six showed that superior strength adaptations occurred as a result of training with accentuated-eccentric loading, whilst also facilitating improvements in eccentric knee extensor moments, that are not achieved with traditional loading. Furthermore, increases in eccentric neural activity were also only increased in the participants who performed accentuated-eccentric loading. Combined, the data presented in chapter six demonstrate that accentuated-eccentric loading is an effective resistance training methodology, that enables superior, or at least equivalent, resistance training adaptations compared to traditional loading paradigms.

In summary, all of the aims outlined in chapter one of this thesis have been achieved. The findings presented in chapters three, four, five and six have significantly added to the present literature within the fields of biomechanics, and S&C. The data presented within this thesis will have a significant impact on future research and current applied practice.

7.2 General Discussion

Throughout this thesis, and in particular in chapter two, it has been highlighted that there is a dearth in research which has examined the eccentric phase of the squat in regards to both movement dynamics and the subsequent adaptations from manipulating the eccentric phase of squatting. The three primary experiments undertaken in this thesis have provided novel findings which have helped to expand the pre-existing literature in several distinct research areas including; the force-velocity relationship, squatting movement kinetics, kinematics and muscle activity, and eccentric-specific strength adaptations, all of which can improve the implementation of S&C practices within strength-trained populations. Additionally, owing to the work described in chapter three, this thesis has also validated the use of the Kineo Training system for the application of performing the squat exercise under constant external loading conditions and under isovelocity conditions, enabling its use in both applied practice and for future investigational research.

The first primary experimental chapter of the thesis began by examining the force-velocity relationship, which is an integral component of skeletal muscle function and dictates the upper bounds of maximum force generation during a given action (Alcazar et al., 2019). As mentioned in chapter one, many S&C coaches utilise eccentric resistance training methodologies based on the presumption that greater forces are produced during eccentric actions (Harden et al., 2020a), with eccentric forces being up to 1.8 times that of isometric force (ex-vivo) and 1.0 to 1.3 times that of an isometric joint moment (single-joint, in-vivo) (Alcazar et al., 2019). However, the data that was presented in chapter four, demonstrates that eccentric GRFs (recorded at -0.75 $m \cdot s^{-1}$) were only 1.1 times that of isometric during an isovelocity squat. The attenuation of the expected eccentric forces is likely down to the complexity of co-ordinating a multi-jointed movement compared to a single-jointed movement, both in terms of the greater degrees of freedom (Kornecki and Zschorlich, 1994, Wuebbenhorst and Zschorlich, 2011, Wuebbenhorst and Zschorlich, 2012) and neural control (Behm et al., 2003, Maffiuletti et al., 2016). Although these data are important novel findings by themselves, the implications suggest that the ability to produce eccentric forces during multi-jointed movements are significantly lower than previously thought, and thus the mechanical stimuli from eccentric resistance training may not be as great as is currently believed.

This was subsequently followed up and discussed in chapter five, where instead of examining maximal eccentric forces, the experimental design investigated the eccentric-joint moments as they were presented under traditional loading conditions (20 to 100% of 1RM) and under accentuated-eccentric loading conditions (100 to 150% 1RM). Hereby it was demonstrated that eccentric joint moments were actually always lower than the concentric joint moments (when equivalent load was used in both the concentric and eccentric phase), which appears to contradict the force-velocity relationship. However, it must be remembered than when training with a constant external load, rather than under isovelocity conditions the acceleration effects of gravity must be considered. During the concentric phase, the opposing force from gravity needs to be overcome in order to lift the load, whilst this is not applicable during the eccentric phase, thereby meaning that maximum volitional effort is not required to perform eccentric squat.

This may suggest that under traditional loading conditions (e.g., 80% 1RM) the eccentric phase does not elicit a substantial level of mechanical tension (which is required to stimulate skeletal muscle adaptation (Rindom et al., 2019, Schoenfeld, 2010a)). Upon inspection of the data presented in chapter five, it appears that the peak knee extensor joint moment that occurs during the eccentric phase of a squat with 80% 1RM is equivalent to the peak knee extensor joint moment that occurs during the concentric phase of a squat with 40% 1RM, which is far below the recommended loading paradigms for both strength and hypertrophy adaptations (Ratamess et al., 2009, Morton et al., 2019). This could explain why the data presented in chapter six identified that participants who performed traditionally loaded squats with an eccentric load of 80% showed no improvement in eccentric strength following 6 weeks of resistance training.

However, the data presented in chapter five identified that accentuated-eccentric loading can increase the peak knee joint moment, with the data suggesting that an eccentric load of 120% 1RM would be optimal. An eccentric load of 120% 1RM produced an eccentric knee joint moment that is equivalent to the concentric knee joint moment produced at 80% 1RM. In contrast to traditional loading, the data presented in chapter six showed that accentuated-eccentric loading did facilitate improvements in eccentric strength following the 6 weeks of resistance training. In terms of eccentric-specific strength adaptations the conclusion is clear, traditional resistance training loading paradigms are not sufficient to elicit an eccentric adaptation in strength-trained populations. If improvements in eccentric strength are required, the research discussed in this thesis suggests that accentuated-eccentric loading is required, and that a starting load of 120% of 1RM should be utilised in the eccentric phase in the squat.

7.3 Practical Applications

From the several data sets presented within this thesis, numerous practical implications can be drawn.

1. Due to this work, applied practitioners who utilis the Kineo technology, can be confident that the squats performed on the Kineo are replicable to those performed with a barbell, and that it is safe to perform eccentrically loaded activities. Work such as that described throughout this thesis is important, as there is an ever growing area of resistance training technology dubbed ‘smart-training systems’ (West et al., 2009), and these technologies should be validated for both their effectiveness and safety prior to implementation into applied practice.
2. The data presented in chapter five suggests that under traditional loading paradigms, the eccentric phase is chronically underloaded and that an eccentric load of 80% 1RM would provide the same stimuli (in terms of peak moment) as the concentric phase performed with a load of 40% 1RM. This likely explains why traditional loading does not result in improvements in eccentric strength in strength-trained populations (as demonstrated in chapter six). Therefore, in order to elicit improvements in eccentric strength, the eccentric phase of the squat needs to be modified, with accentuated-eccentric loading being a valid methodology.
3. The squat exercise typically being employed in applied practice to develop all the musculature, and increase the strength, of the lower limbs, particularly the quadriceps (knee extensors) and gluteus (hip extensors (Kubo et al., 2019, Akagi et al., 2020). The data presented in chapter five suggests that utilising accentuated-eccentric loading in squat exercise preferentially loads the knee extensors whilst having little additional

impact on the hip extensors. Therefore, accentuated-eccentric loading should be primarily used in sports that specifically require high levels of knee eccentric extensor strength such as field-based sports which require frequent changes of direction (Jones et al., 2017) and deceleration (Harper et al., 2019)

4. According to the data in chapter five, an eccentric load of 120% 1RM would appear to be optimal in order to elicit eccentric strength adaptations. This was because increases in eccentric loading above this (up to 150% 1RM) do not lead to significant increase in peak joint moments. Therefore, increase the eccentric load above 120% would not appear to provide any benefit, but might increase the risk of injury due to an increase load (Schoenfeld, 2010b).
5. Prior to this thesis, there has been an interest for more information pertaining to the effects of accentuated-eccentric loading on fatigue and muscle soreness (Harden et al., 2020a). The data presented in chapter six has clearly demonstrated that although a single bout of accentuated-eccentric loading produces greater scoring of DOM and RPE, these are attenuated following four weeks of training, and are then in line with the scoring of traditional resistance training. Therefore, practitioners should carefully plan where they include accentuated-eccentric loading within a periodised training programme.
6. Finally, in chapter six, a six-week long resistance training programme that utilised accentuated-eccentric loading in a fundamental exercise pattern has been described, including criteria on how to progress session to session. This training programme has been thusly proven to elicit eccentric-specific strength adaptations, superior improvements in squat 1RM and equivalent improvements in concentric and isometric strength compared to traditional resistance training. This programme can be replicated and implemented by applied practitioners.

7.4 Limitations

This thesis has presented several novel findings, as well as added to existing bodies of research in the fields of biomechanics and S&C. In additional it has provided key information for applied practitioner that will enable them to develop applicable S&C programmes. The data presented here has also been communicated in five conferences presentations, as well as two peer-reviewed publications. However, no study is without its limitations. During this section, the main limitations of each study will be outlined.

7.4.1 Determining Concentric and Eccentric Force-Velocity Profiles During Squatting

The first experimental study of this thesis examined the force-velocity relationship during concentric and eccentric squatting under isovelocity conditions. In chapter three, initial data was discussed which explained the selection of the velocities used to assess the force-velocity relationship in chapter four. Only three velocities were selected for each of the concentric and eccentric phases, with a maximum eccentric velocity being $-0.75\ \mathrm{m \cdot s^{-1}}$. In this study it was not possible to explore the maximum eccentric forces past this range, as this was the maximum safe operating range of the Kineo. Therefore, it is unknown if greater eccentric forces could have been achieved or if eccentric forces would have declined as eccentric velocity increased. Secondly, no direct measures of isometric force were taken, rather an estimate of isometric force was calculated for zero velocity from a cubic polynomial regression equation fitted to each participant's measured force-velocity profile. Calculating isometric force in this manner has been previously used (Morin and Samozino, 2016, Samozino et al., 2010) and shown to be robust.

7.4.2 Determining Movement Dynamics and Muscle Activity During the Eccentric Phase of Squatting with Traditional and Accentuated-Eccentric Loading

The second primary study of this thesis examined movement dynamics and muscle activity during squatting. Due to extenuating circumstances this study was unfortunately able to collect data from only nine of the fifteen recruited participants. This was a result of restrictions placed on participant-facing research during the COVID-19 pandemic in 2020. Despite this, the study still obtained more than the minimum required participants for statistical power (see chapter five, section 5.2). Secondly, this study also initially planned to assess maximal voluntary contractions of the hip, knee, and ankle extensors in order to identify the relative muscular effort (Bryanton et al., 2012). However, this portion of data collection was not achieved prior to the aforementioned COVID-19 restrictions. Therefore, it was not possible to normalise peak joint moments in terms of their maximum capabilities. Regardless, this did not impact on the interpretation of the data presented in chapter, as alternative comparators were utilised. Thirdly, during this study, surface electrodes and reflective markers were required to be placed on the participants to facilitate recording of muscle activity and to record kinematic data, respectively. However, the participants had to wear a shoulder/hip harness (see chapter three for details) in order to be connected to the Kineo. This therefore limited where electrodes and markers could be placed. As a result, no muscle activity or kinematics data could be measured from the trunk, nor could electrodes be placed on the vastus medialis. However, the lack of this data does not distract from the novel findings that were presented in chapter five.

7.4.3 Assessment of the Effectiveness of Accentuated-Eccentric Loading in Comparison to Traditional Loading in The Squat

In the final experimental chapter, 22 strength-trained male participants completed a six-week long resistance training intervention consisting of 12 exercise sessions. Although this time frame was long enough in duration to elicit adaptations in muscular strength, minimal adaptations were observed for muscle architecture, with only a 0.8mm increase in vastus lateralis thickness observed. It has previously been shown that strength-trained populations have an attenuated response to resistance training compared to untrained populations (Ahtiainen et al., 2003), which results in strength-trained populations requiring a greater number of resistance training sessions to elicit a measurable hypertrophic response (Lopez et al., 2021). Therefore, it is likely that the training intervention was not of sufficient duration to observe measurable changes in muscle architecture, in particular to pennation angle and fascicle length.

Secondly, during this study it was impossible to blind the participant to whether they were in the traditional resistance training group or accentuated eccentric loading groups. This could have led to participant in the traditional group to put in less than maximal effort during the post-testing. However, we do not believe this is the case for all testing, in particular due to the stability of the EMG from pre to post-testing during the assessment of knee joint moments, and the education level/experience of the participants.

7.5 Recommendations For Future Research

In this thesis, several studies were conducted, with applications in biomechanics and S&C. These novel findings will significantly expand the aforementioned research areas. However, many research questions remain unanswered. Below are several propositions for future research based on the finding discussed in this thesis.

In chapter four, novel data on the squat force-velocity relationship was presented and discussed. To date, those data were the first true representation of the maximum voluntary forces that could be produced during the squat exercise, and the second study which has examined the force-velocity relationship in a multi-jointed lower body exercise (Hahn, 2018). However, in chapter four, only data examining the ground rection forces were presented, whereas these forces are a product of the hip, knee and ankle extensors. Therefore, future research should aim to also assess the joint moments produced during isovelocity squatting. In addition, it would be beneficial to then compare the joint moments produced during isovelocity squatting to those produced during isolated single-joint maximal voluntary contractions. This would enable the research to identify the percentage of their maximum capabilities the hip, knee, and ankle extensors are working at.

In chapter five, novel data on the movement dynamics and muscle activity during the eccentric phase of the squat were discussed. In this data set, the greatest load that was assessed was 150% of 1RM. However, the joint moments produced at this load were lower than the joint moments produced concentrically. Considering the data presented in chapter four and the wider research area on the force-velocity relationship (Alcazar et al., 2019), it is known that eccentric forces can exceed concentric forces. Therefore, in the present study, the loads selected did not facilitate maximum eccentric capabilities. Future research may therefore wish to assess the maximum loads that are capable of being used in the eccentric phase, however caution must be taken in doing so due to the increased safety risk of using such large external loads.

Future research may also wish to compare the measured joint moments as they were presented during the eccentric phase of the squat to maximum voluntary contractions performed on an isokinetic dynamometer to determine the relative muscular effort, which has previously been performed during the concentric phase of the squat (Bryanton et al., 2012).

The final experimental chapter in this thesis compared three 6-week long resistance training interventions, two with accentuated-eccentric loading, and one under traditional loading paradigms. This study attempted to volume match the two accentuated-eccentric groups to the traditional group in two manners, first by total number of repetitions and secondly by total work. This resulted in one group performing four sets of six, and the other three sets of six. Despite being scientifically sound, there was little actual difference in volume, and thus it was unsurprising that no differences were found between the two accentuated-eccentric groups in any outcome measures. Future research should aim to see if a low volume approach to accentuated-eccentric training can still elicit eccentric-specific adaptations.

The data presented in chapter six also clearly demonstrated that eccentric-specific increases in strength were obtained only by participants who performed accentuated-eccentric loading. Previous research has demonstrated that eccentric-specific adaptations can be maintained for 4 weeks following detraining (Presland et al., 2018), however, it is unknown how long this effect last for with complete detraining, or if participants can maintain these adaptations once they return to traditional resistance training. The length of time that these adaptations last for have implication on the timing of utilising accentuated-eccentric loading within a periodised training programme, therefore it is important to identify the time-course of these adaptations in order to facilitate long term training program design.

Finally, the data presented in chapter six also noted that there was an attenuation of DOMS and RPE following eight bouts of accentuated-eccentric loading. However, it is unknown how long this effect lasts for following cessation of accentuated-eccentric loading. Neither is it known if this attenuation is specific to the task of squatting or if it can translate to an attenuation of DOMS in other sporting activities such as field-based sports. Both of which have implications upon the implementation of accentuated-eccentric loading within applied practice. In order to improve the strength of these measures, it would also be worthwhile to collect objective markers of muscle damage and inflammation rather than relying of subjective scores.

7.6 Conclusion

This thesis set out to improve the understanding of the underpinning movement dynamics during accentuated-eccentric loading in the squat and to identify if accentuated-eccentric loading could be a viable resistance training methodology in previously strength-trained populations.

A series of experiments were undertaken which identified that the eccentric phase of the squat was likely a providing sub-optimal stimulus for adaptation under traditional loading paradigms.

This was demonstrated by the peak joint moments produced during the eccentric phase of the squat (when using a load of 80% of 1RM) being equivalent to the concentric joint moments at 40% 1RM. The difference in eccentric and concentric joint moments is overcome when accentuated-eccentric load is incorporated, with a load of 120% appearing optimal. Training with an accentuated-eccentric load resulted in superior improvements in squat 1RM, and eccentric-specific improvements in knee extensor strength that were not observed following traditional resistance training. The data presented here will help to inform future applied practice by informing the prescription of accentuated-eccentric loading.

The novel data presented throughout this thesis has achieved the aims set out at the start of this thesis. In addition to being presented in this thesis, these data have been presented at national and international conferences, and have been published in peer reviewed journals.

Chapter 8.

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Chapter Nine.

Appendices

9.1 Description of the RAMP Warmup

The RAMP warmup is a framework for designing warmups to aid in physical preparation and was developed by (Jeffreys, 2006). This style of warmup was used through this thesis. Below is the detailed version of the warm up that was used.

Stage 1. Raise

- Participants would perform five minutes of cycling on a cycle ergometer at a wattage equal to 1 watt·kg^{-1}.

Stage 2. Activate and Mobilise

- Participants would perform two sets of 10 repetitions of the following unweighted whole-body movements – bodyweight squat, ingle-leg standing hip hinge, & reverse lunge

Figure 9-1Demonstration of the squat movement used in the RAMP warmup

Figure 9-2 Demonstration of the single-leg standing hip hinge movement used in the RAMP warmup

Figure 9-3 Demonstration of the reverse lunge movement used in the RAMP warmup

Stage 3. Potentiate

- The third stage of the RAMP warmup (potentiate) would depend on the particulars of the specific session. However, this typically involved squats performed on the Kineo at a variety of loads. For specific details, refer to the methods section in each chapter.

9.2 Rating of Perceived Exertion Scale

In several sections of this thesis, it was necessary to take a measurement of rating of perceived exertion. The follow scale was used, which was validated in Zourdos et al. (2016).

Rating	**Description of Perceived Exertion**
10	*Maximum Effort*
9.5	*No Further reps, but could increase weight*
9	*1 repetition remaining*
8.5	*1-2 repetitions remaining*
8	*2 repetitions remaining*
7.5	*2-3 repetitions remaining*
7	*3 repetitions remaining*
5-6	*4-6 repetitions remaining*
3-4	*Light effort*
1-2	*Little to no effort*

9.3 Delayed Onset of Muscle Soreness visual analogue scale

In several sections of this thesis, it was necessary to take a measurement of delayed onset of muscle soreness The follow visual analogue scale was used, which was validated in (Cleather and Guthrie, 2007).