ACUTE NEUROMUSCULAR, KINETIC, AND KINEMATIC RESPONSES TO ACCENTUATED ECCENTRIC LOAD RESISTANCE EXERCISE

By

THOMAS GRANT BALSHAW

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School of Sport
University of Stirling
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DEDICATION

This thesis is dedicated to the memory of my grandmother, Anne Feeley. I'm overcome with sadness when I think that you are not here to see me complete this journey. You will never be forgotten.

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THESIS ABSTRACT

Neurological and morphological adaptations are responsible for the increases in strength that occur following the completion of resistance exercise training interventions. There are a number of benefits that can occur as a result of completing resistance exercise training interventions, these include: (i) reduced risk of developing metabolic health issues; (ii) decreased risk and incidence of falling; (iii) improved cardiovascular health; (iv) elevated mobility; (v) enhanced athletic performance; and (vi) injury prevention. Traditional resistance exercise (constant load resistance exercise (CL)) involves equally loaded eccentric and concentric phases, performed in an alternating manner. However, eccentric muscle actions have unique physiological characteristics, namely greater force production capacity and lower energy requirements, compared to concentric actions. These characteristics have led to the exploration of eccentric-focused resistance exercise for the purposes of injury prevention, rehabilitation, and enhancement of functional capacity.

Accentuated eccentric load resistance exercise (AEL) is one form of eccentric-focused resistance exercise. This type of resistance exercise involves a heavier absolute external eccentric phase load than during the subsequent concentric portion of a repetition. Existing training study interventions comparing AEL to CL have demonstrated enhancements in concentric, eccentric, and isometric strength with AEL. However, no differences in strength adaptations have been reported in other AEL *vs.* CL training studies. Only 7 d intensified AEL training interventions have measured neuromuscular variables, providing evidence that enhanced neuromuscular adaptations may occur when AEL is compared to CL. Therefore, a lack of information is currently available regarding how AEL may differentially affect neuromuscular control when compared to CL. Furthermore, the equivocal findings regarding the efficacy of AEL make it difficult for exercise professionals to decide if they should employ AEL with their athletes or patients and during which training phase this type of resistance exercise could be implemented. Therefore, the aims of this thesis were: (i) to examine differences in acute neuromuscular, kinetic, and kinematic responses between AEL and CL during both lower-body single-joint resistance exercise and multiple-joint free weight resistance exercise; (ii) to assess acute force production and contractile characteristics following AEL and CL conditions; (iii) to investigate the influence of eccentric phase velocity (and time under tension) on acute force production and contractile characteristics following AEL and CL conditions; and (iv) to compare common drive and motor unit firing rate responses after single- and multiple-joint AEL and CL.

Before investigating neuromuscular, kinetic, and kinematic responses to AEL it was deemed necessary to evaluate normalisation methods for a multiple-joint free weight resistance exercise that would permit the implementation of AEL. Therefore, the aim of the first study of the thesis was to evaluate voluntary maximal (dynamometer- and isometric squat-based) isometric and submaximal dynamic (60%, 70%, and 80% of three repetition maximum) electromyography (EMG) normalisation methods for the back squat resistance exercise. The absolute reliability (limits of agreement and coefficient of variation), relative reliability (intraclass correlation coefficient), and sensitivity of each method was assessed. Strength-trained males completed four testing sessions on separate days, the final three test days were used to evaluate the different normalisation methods. Overall, dynamic normalisation methods demonstrated better absolute reliability and sensitivity for reporting vastus lateralis and biceps femoris EMG compared to maximal isometric methods.

Following the methodological study conducted in Chapter 2, the next study began to address the main aims of the thesis. The purpose of the third chapter of the thesis was to compare acute neuromuscular, kinetic, and kinematic responses between single-joint AEL and CL knee extension efforts that included two different eccentric phase velocities. Ten males who were completing recreational resistance exercise attended four experimental test day sessions where knee extension repetitions (AEL or CL) were performed at two different eccentric phase velocities (2 or 4 s). Elevated vastus lateralis eccentric neuromuscular activation was observed in both AEL conditions (p= 0.004, f= 5.73). No differences between conditions were detected for concentric neuromuscular or concentric kinematic variables during knee extension efforts. Similarly, no differences in after-intervention rate of torque development or contractile charactersitics were observed between conditions.

To extend the findings of the third chapter of the thesis and provide mechanistic information regarding how AEL may differentially effect acute neuromuscular variables that have been reported to be undergo chronic adaptations, additional measures that were taken before and after the intervention described in the previous chapter were analysed. Therefore, the purpose of the fourth chapter of the thesis was to compare motor unit firing rate and common drive responses following single-joint AEL and CL knee extension efforts during a submaximal isometric knee extension trapezoid force trace effort. In addition, motor unit firing rate reliability during the before-intervention trapezoid force trace efforts was assessed. No differences in the maximum number of detected motor units were observed between conditions. A condition-time-point interaction effect (p= 0.025, f= 3.65) for firing rate in later-recruited motor units occurred, with a decrease in firing rate observed in after-intervention measures in the AEL condition that was completed with a shorter duration eccentric phase. However, no differences in common drive were detected from before- to after-intervention measures in any of the conditions. The time period toward the end of the plateau phase of before-intervention trapezoid force trace efforts displayed the greatest absolute and relative reliability and was therefore used for motor unit firing rate and common drive analysis.

The purpose of the fifth chapter was to compare acute neuromuscular and kinetic responses between multiple-joint AEL and CL back squats. Strength-trained males completed two experimental test day sessions where back squat repetitions (AEL or CL) were performed. Neuromuscular and kinetic responses were measured

during each condition. No differences in concentric neuromuscular or concentric kinetic variables during back squat repetitions were detected between conditions. Elevated eccentric phase neuromuscular activation was observed during the AEL compared to the CL condition in two to three of the four sets performed for the following lower-body muscles: (i) vastus lateralis (p< 0.001, f= 15.58); (ii) vastus medialis (p< 0.001, f= 10.77); (iii) biceps femoris (p= 0.003, f= 6.10); and (iv) gluteus maximus (p= 0.001, f= 7.98). There were no clear differences in terms of the neuromuscular activation contributions between muscles within AEL or CL conditions during eccentric or concentric muscle actions.

Following the investigation of acute motor unit firing rate and common drive responses to lower limb single-joint AEL and CL in the fourth chapter of the thesis, the question arose as to whether or not similar responses would occur in a more complex model, such as a multiple-joint resistance exercise. Multiple-joint resistance exercise poses different neuromuscular activation, coordination, and stabilisation demands. Therefore, the purpose of the sixth chapter of the thesis was to compare acute motor unit firing rate and common drive responses following multiple-joint lower-body free weight AEL and CL. In addition, motor unit firing rate reliability during the before-intervention trapezoid force trace efforts, performed on a custom-built dynamometer, was assessed. No differences in motor unit firing rate or the number of motor units detected were observed between conditions. Condition-time-point interaction effects were observed for maximum peak cross-correlation coefficients (p= 0.028, f= 8.24), with a decrease from before to after intervention measures in the CL condition. However, differences in mean peak cross-correaltion coefficients and cross-correlation histogram distributions were not detected between conditions. As in Chapter 4 the time period toward the end of the plateau phase of before-intervention trapezoid force trace efforts displayed the greatest absolute reliability and was therefore used for motor unit firing rate and common drive analysis. Whereas, relative reliability was shown to be “poor” across all time phases.

The results of the studies that comprise this thesis contribute new knowledge to the AEL research literature. In particular, the way that motor unit recruitment strategy responses were investigated following interventions provided new information regarding the acute neuromuscular effects of AEL and a new potential approach to investigating the hypothesised similarities between motor learning and resistance exercise. Previously, only transcranial magnetic stimulation had been used for this purpose. However, the contrasting motor unit firing rate and common drive response results of Chapter 4 and 6 of the thesis indicate further research is required to ascertain how acute measures quantified through the decomposition of surface EMG (such as motor unit firing rate and common drive) are related to chronic neuromuscualr adaptations following resistance exercise.

The findings presented in the thesis also add to the existing body of AEL research literature by providing practitioners with novel data regarding the acute neuromuscular, kinetic, and kinematic responses during AEL. The results presented in Chapter 3 and 5 of the thesis suggest that AEL resistance exercise implemented in both single- and multiple-joint resistance exercise models presents no negative acute variable responses. Neither of the AEL models investigated acutely reduced concentric kinetic outputs, decreased neuromuscular contributions or activation from key agonist muscles during concentric or eccentric phases, or caused after-intervention lower-body force production or contractile characteristics to decline more than following CL. In addition, both AEL models involved greater eccentric phase knee extensor muscle contributions compared to CL. Therefore, given these findings exercise professionals who prescribe training interventions may want to consider the use of AEL depending on the characteristics and training goals of the individuals they work with. Despite these encouraging acute neuromuscular, kinetic, and kinematic responses to AEL further research is clearly required to confirm the efficacy of AEL on a longitudinal basis. Specifically, the efficacy of AEL for the concurrent enhancement of both chronic concentric and eccentric knee and hip extensor strength, eliciting chronic neuromuscular adaptations in these muscles, and preventing injury in a range of populations remains unclear.

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ABBREVIATIONS

3RM	Three repetition maximum
AEL	Accentuated eccentric load resistance exercise
AEL-2s	Accentuated eccentric load resistance exercise performed with a target 2 s eccentric phase
AEL-4s	Accentuated eccentric load resistance exercise performed with a target 4 s eccentric phase
CL	Constant load resistance exercise
CL-2s	Constant load resistance exercise performed with a target 2 s eccentric phase
CL-4s	Constant load resistance exercise performed with a target 4 s eccentric phase
EMG	Electromyography
MIS	Maximal voluntary isometric squat
MVC	Maximal voluntary isometric contraction

THESIS INTRODUCTION

The completion of resistance exercise training interventions leads to neurological (Gabriel et al., 2006), morphological (Folland and Williams, 2007), and skeletal adaptations (Snow-Harter et al., 1992). Such adaptations include increases in muscular strength, muscle mass, and bone mineral density. Consequently, the effect of resistance training on health and functional outcomes has been investigated in clinical, general, and athletic populations. Resistance exercise has been shown to reduce the risk of developing metabolic disease (Grontved et al., 2012), decrease the risk (Liu-Ambrose et al., 2004) and incidence of falling (Rubenstein et al., 2000; Campbell et al., 1999; Campbell et al., 1997; Buchner et al., 1997), improve cardiovascular health (Cornelissen and Fagard, 2005; Kelley and Kelley, 2000), benefit mobility and activities of daily living (Lastayo et al., 2010; Dibble et al., 2009; Lastayo et al., 2009; Dibble et al., 2006; Lastayo et al., 2003a), enhance athletic performance (Channell and Barfield, 2008; Myer et al., 2005), and reduce injury (Petersen et al., 2011; Askling et al., 2003). Previously, numerous resistance exercise variables have been investigated with the aim of ensuring optimal practices for achieving adaptation.

Eccentric-focused resistance exercise has received particular attention, given the greater force producing capabilities and lower energy requirements of eccentric muscle actions. These physiological characteristics have led to the suggestion that during traditional constant load resistance exercise (CL) eccentric muscle actions are undertrained, compared to concentric actions (Hortobagyi et al., 2001a). Consequently, the potential uses of resistance exercise employing eccentric-only, heavy, or supramaximal eccentric loads (accentuated eccentric load resistance exercise (AEL)) have been investigated. Contrasting results currently exist regarding the effectiveness of lower-body AEL for enhancing chronic strength adaptations beyond that of CL. Existing lower-body training intervention studies comparing AEL to CL have demonstrated superior enhancements in concentric (Brandenburg and

Docherty, 2002; Hortobagyi and Devita, 2000; Nichols et al., 1995), eccentric (Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000), and isometric (Norrbrand et al., 2008; Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000) strength with AEL. Therefore, indicating AEL can be a beneficial training practice. However, no differences in strength adaptations have been reported in other AEL *vs.* CL training intervention research (Friedmann-Bette et al., 2010; Yarrow et al., 2008; Godard et al., 1998; Ben-Sira et al., 1995; Nichols et al., 1995). Additionally, uncertainty remains over which mechanisms may be responsible for the superior strength gains that can occur with AEL. As a result of the equivocal training programme intervention reports, regarding chronic strength gains, it is currently difficult for practitioners to ascertain the efficacy of implementing AEL training interventions with different populations. These contrasting results are compounded by a lack of measures assessing neuromuscular adaptation, beyond intensified 7 d training interventions.

The lack of clarity regarding the efficacy of lower-body AEL, as a result of the current training intervention literature investigating this type of resistance exercise, may be addressed, in part, by acute studies comparing neural responses between AEL and CL. Recent research supports the hypothesis that resistance exercise is similar to motor learning (Selvanayagam et al., 2011; Carroll et al., 2001). Therefore, indicating acute neural responses during and after resistance exercise may provide an indication of the nature of the chronic strength adaptations following a training intervention. To date, no acute lower-body AEL studies have compared neuromuscular variables to equivalent CL conditions, whilst simultaneously measuring kinetic or kinematic output. Therefore, research comparing acute neuromuscular activation and detailed recruitment strategy responses, during and following AEL, may be particularly informative. Specifically, such studies could help exercise professionals to decide whether or not to employ AEL with their athletes or patients and also provide important mechanistic information to understand how AEL might influence chronic strength adaptations. However, before identifying specific research questions that would provide novel physiological data from the investigation of eccentric-focused resistance exercise (and specifically AEL), it was necessary to conduct a review of the current applications of eccentric-focused resistance exercise for the purposes of injury prevention, rehabilitation and enhancement of functional capacity.

CHAPTER 1

LITERATURE REVIEW

CURRENT APPLICATIONS OF ECCENTRIC-FOCUSED RESISTANCE EXERCISE FOR INJURY PREVENTION, REHABILITATION, AND ENHANCEMENT OF FUNCTIONAL PERFORMANCE

1.1 Introduction

Resistance exercise typically involves the completion of dynamic muscle actions against external loads. The repeated performance of acute resistance exercise training sessions, such as within a progressive training programme intervention, leads to chronic neurological (Gabriel et al., 2006), morphological (Folland and Williams, 2007) and skeletal adaptations (Snow-Harter et al., 1992). Such adaptations ultimately lead to increases in muscular strength, muscle mass and bone mineral density. Consequently, the effect of resistance exercise training on health and functional outcomes has been investigated in a range of populations.

These chronic adaptations following resistance exercise training interventions can: (i) reduce the risk of developing metabolic health issues (Grontved et al., 2012); (ii) decrease the risk (Liu-Ambrose et al., 2004) and incidence (Rubenstein et al., 2000; Campbell et al., 1999; Campbell et al., 1997; Buchner et al., 1997) of falling; (iii) improve cardiovascular health (Cornelissen and Fagard, 2005; Kelley and Kelley, 2000); (iv) increase functional mobility and activities of daily living

(Lastayo et al., 2010; Dibble et al., 2009; Lastayo et al., 2009; Dibble et al., 2006; Lastayo et al., 2003a); (v) enhance athletic performance (Channell and Barfield, 2008; Myer et al., 2005); (vi) prevent injury (Petersen et al., 2011; Askling et al., 2003); and (vii) be used to rehabilitate following injury (Gerber et al., 2007a; Gerber et al., 2007b; Gerber et al., 2006; Coury et al., 2006). These health and functional changes are of benefit to clinical, general, and athletic populations.

Previously, numerous variables within resistance exercise training programmes, have been investigated in order to develop optimal practices for achieving physiological adaptations. These variables include: (i) training frequency (Rhea et al., 2003); (ii) training volume (Rhea et al., 2003); (iii) rest period duration (Ratamess et al., 2012a; Ratamess et al., 2012b; Willardson and Burkett, 2008; Ratamess et al., 2007; Willardson and Burkett, 2006a; Willardson and Burkett, 2006b); (iv) load (Rhea et al., 2003); and (iv) the type of muscle actions used (Moore et al., 2012; Vikne et al., 2006; Higbie et al., 1996; Duncan et al., 1989; Komi and Buskirk, 1972). The combination of muscle actions employed during resistance exercise has received particular attention (Roig et al., 2009; Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000; Colliander and Tesch, 1990). Specifically, it has been identified that eccentric muscle actions have greater force producing capabilities (Elftman, 1966) and lesser energy requirements (Abott et al., 1952), compared to concentric muscle actions. These physiological characteristics have led to the suggestion that eccentric muscle actions are undertrained during traditional CL (Hortobagyi et al., 2001a). Concentric muscle actions involve shortening of the musculotendinous unit, whereas eccentric actions involve lengthening of the unit against external force. Both of these muscle actions can be performed during a typical resistance exercise. However, the unique characteristics of eccentric muscle actions have led to the potential uses of resistance exercise employing eccentric-only, heavy, or supramaximal eccentric loads being investigated. Given that the focus of this chapter was to examine the applications of eccentric-focused resistance exercise it was beyond the scope of this literature review to examine existing research investigating skeletal muscle damage responses to single or repeated bouts of eccentric exercise. The purposes of this chapter were threefold. Firstly, to review the current rehabilitation, injury prevention, and functional applications of resistance exercise involving: (i) only eccentric muscle actions; and (ii) heavier eccentric compared to concentric phase loads. Secondly, to detail the physiological mechanisms supporting the use of eccentric-focused resistance exercise for its current applications. Thirdly, to identify future studies that may potentially add to the existing body of eccentric-focused resistance exercise research.

1.2 Physiology of eccentric muscle actions

Before reviewing the current uses of eccentric-focused resistance exercise, the unique physiological characteristics of eccentric muscle actions are briefly summarised. These unique characteristics have led to the exploration of eccentric-focused resistance exercise in the following range of health and functional performance applications that will be discussed in this chapter. Eccentric muscle actions display greater force production capabilities and lower energy requirements than concentric muscle actions. The Elftman proposal (Elftman, 1966) describes a force production hierarchy, such that eccentric muscle actions produce greater force than both isometric and concentric actions. The greater force production during eccentric muscle actions has been postulated to be due to: (i) unique neuromuscular activation strategies (Nardone et al., 1989; Nardone and Schieppati, 1988); (ii) development of tension through the elastic component of the myosin contractile protein filaments and parallel elastic component (Huxley, 2000; Curtin and Woledge, 1981); and (iii) rapid repeated reformation of cross bridges following detachment (Flitney and Hirst, 1978; Joyce et al., 1969).

Resistance exercise performed with a constant absolute external load involves the completion of both concentric and eccentric muscle actions. However, lower levels of neuromuscular activation have been consistently displayed during eccentric muscle actions (Grabiner and Owings, 2002; Madeleine et al., 2001; Kay et al., 2000; Westing et al., 1991; Moritani et al., 1987; Bigland and Lippold, 1954). Two explanations have been offered for the lower neuromuscular activation observed during eccentric actions: (i) unique neuromuscular recruitment strategies (Howell et al., 1995; Nardone et al., 1989; Nardone and Schieppati, 1988); and (ii) passive force generation from the parallel and series elastic components (Kossev and Christova, 1998; Curtin and Woledge, 1981; Huxley and Peachey, 1961). The passive force generated from parallel and series elastic structures may reduce the amount of neuromuscular activation required to meet force production demands during eccentric muscle actions. Previously, studies investigating eccentric neuromuscular activation have suggested large, high threshold motor units are preferentially recruited and lower threshold motor units are derecruited during such actions (Howell et al., 1995; Nardone et al., 1989; Nardone and Schieppati, 1988). The concept of unique eccentric neuromuscular recruitment strategies has gathered support as a result of studies demonstrating different recruitment patterns (Nardone et al., 1989; Nardone and Schieppati, 1988), observations of smaller motor evoked potentials (Abbruzzese et al., 1994), delayed motor evoked potential recovery time (Tallent et al., 2012), and reduced H-reflex responses (Abbruzzese et al., 1994; Romano and Schieppati, 1987) during eccentric compared to concentric muscle actions. Reduced motor neuron pool excitability at the motor cortex (Abbruzzese et al., 1994) or the spinal cord (Enoka, 1996) have been postulated to explain the smaller motor evoked potential and H-reflex responses observed during muscle lengthening. However, the concept of unique eccentric recruitment strategies contradicts the widely accepted Henneman size principle (Henneman et al., 1965) and not all studies have observed differences in neuromuscular recruitment between eccentric and concentric muscle actions (Stotz and Bawa, 2001; Bawa and Jones, 1999).

The theory that greater eccentric force production is a product of reduced eccentric neuromuscular activation and greater force generation contributions from passive elastic components has gained support, from both animal and human model studies (Kossev and Christova, 1998; Curtin and Woledge, 1981; Huxley and Peachey, 1961). Research investigating isolated frog muscle has suggested the elastic component of the myosin contractile filaments and that of the series elastic component contribute to greater force production during eccentric muscle actions (Curtin and Woledge, 1981; Huxley and Peachey, 1961). In addition, it is believed that during eccentric muscle actions in whole intact muscles the parallel elastic components are also responsible for the greater force production observed (Curtin and Woledge, 1981). Furthermore, reduced neuromuscular activation and firing rates have been observed during eccentric actions (Laidlaw et al., 2000; Kossev and Christova, 1998), supporting the concept that passive structures generate force and decrease force production contributions from contractile proteins. Additionally, the role of rapid reattachment of cross bridges following forced detachment during eccentric muscle actions is also postulated to contribute to elevated eccentric force levels (Flitney and Hirst, 1978; Joyce et al., 1969). Controversy continues over which mechanisms, or combination of mechanisms, are responsible for the greater force production during eccentric muscle actions.

With regard to energy requirements, eccentric muscle actions require lower oxygen uptake (Bonde-Petersen et al., 1972; Bigland and Lippold, 1954; Abott et al., 1952), use less phosphocreatine (Ryschon et al., 1997; Wilkie, 1968), and have reduced levels of adenosine triphosphate breakdown (Ryschon et al., 1997; Wilkie, 1968). The lower energy cost of eccentric muscle actions may be due to the lower volume of active muscle mass (Grabiner and Owings, 2002; Madeleine et al., 2001; Kay et al., 2000; Westing et al., 1991; Moritani et al., 1987; Bigland and Lippold, 1954) in combination with reduced adenosine triphosphate hydrolysis. Decreased eccentric adenosine triphosphate hydrolysis occurs as a result of a proportion of muscle tension being generated from the forced detachment of cross bridges (Ryschon et al., 1997). The greater force producing capabilities and lower energy requirements of eccentric muscle actions have led to the eccentric phase being manipulated during resistance exercise in an attempt to benefit various applications including: (i) injury prevention; (ii) rehabilitation; and (iii) functional performance. Eccentric-only and AEL are the two main eccentric-focused resistance exercise variants that have been employed in the existing research literature.

1.3 Distinct types of eccentric-focused resistance exercise

1.3.1 Eccentric-only resistance exercise

Eccentric-only resistance exercise involves the completion of a loaded eccentric muscle action phase followed by an assisted or unloaded concentric phase. This type of resistance exercise allows individuals to complete a loaded eccentric phase whilst also performing multiple repetitions. Although a concentric element remains during eccentric-only resistance exercise, the fact that this phase is assisted or completely unloaded means any concentric phase training effect is likely to be negligible. Eccentric-only resistance exercise can be implemented during: (i) dynamometer resistance exercise; (ii) resistance machine exercise; (iii) body mass-based exercises (e.g. unilateral heel drops (Figure 1.1) and Nordic hamstring exercise (Figure 1.2)); (iv) single- and multiple-joint free weight resistance exercise; or (v) eccentric ergometry (Figure 1.3). The removal of concentric phase load can be achieved by manual removal by assistants, as a function of computer or resistance machine settings, or the performance of the concentric phase by the uninjured limb (such a during unilateral heel drops). Loading during this type of training varies and can range from submaximal intensities based on a percentage of concentric repetition

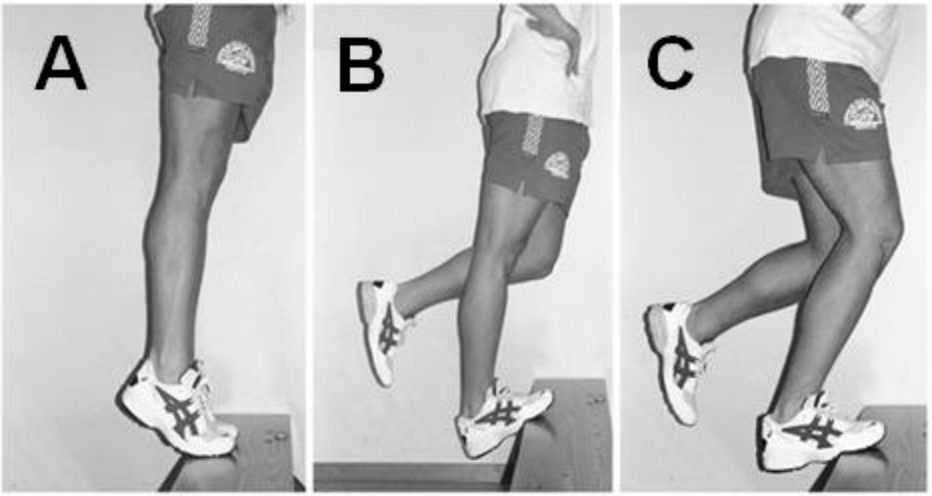


Figure 1.1 A unilateral heel drop exercise. From the start position standing on a bench or step (A) the right leg is used to lower the body with either an extended (B) or bent leg (C). At the bottom of the exercise (B,C) the left leg is placed back on the step and used to perform the concentric portion of the exercise to return to the start position (A). Replicated with permission (Alfredson et al., 1998).

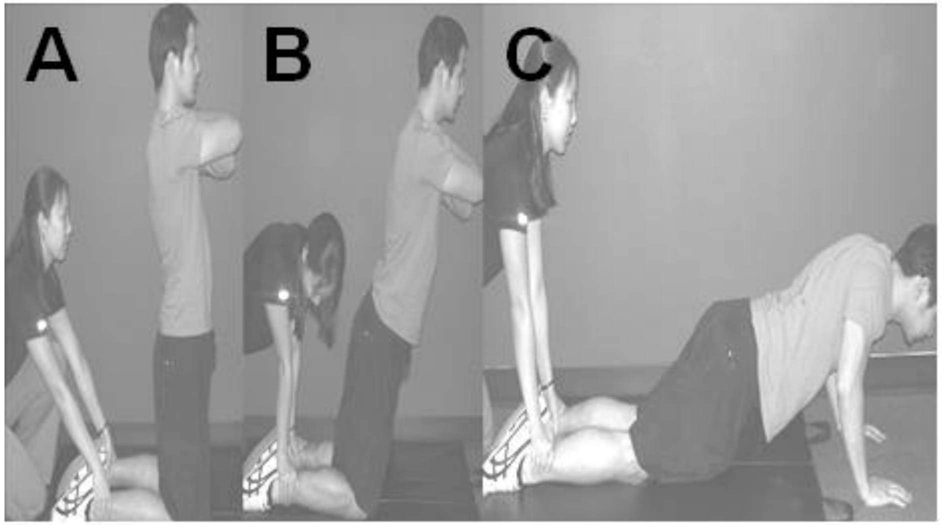


Figure 1.2 The Nordic hamstring exercise. Completed in pairs, one training partner holds the ankles of the other (A), whilst the anchored partner extends their knees (B), lowering them to the ground. The anchored partner then uses their hands to brake their landing (C) and return themselves to the start position for the next repetition (A). Replicated in accordance with U.S. fair use guidelines (Hibbert et al., 2008).

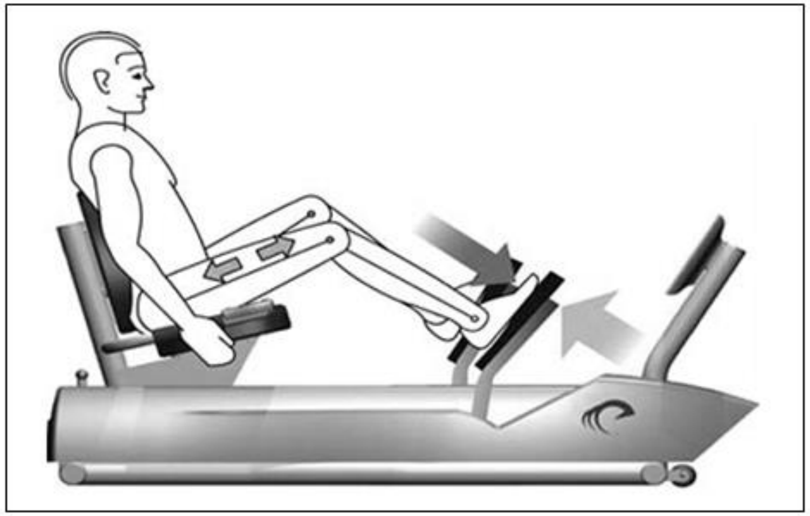


Figure 1.3 Eccentric ergometer. When the pedals move toward the participant the knee extensors are activated to resist the movement of the pedals, as the magnitude of the ergometer exceeds the force produced by the participant the knee extensor muscles undergo eccentric muscle actions. Replicated with permission (Lastayo et al., 2009).

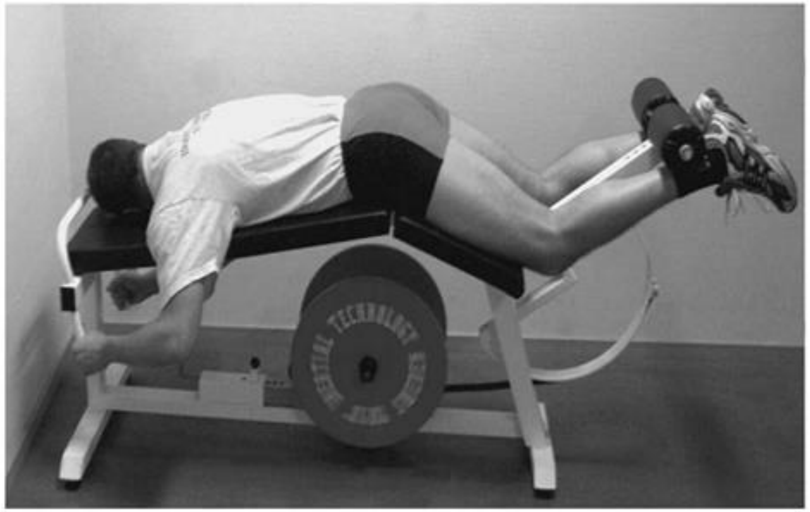


Figure 1.4 Eccentric flywheel leg curl ergometer. Flywheel training devices involve a strap winding and unwinding around a rotating shaft, during the eccentric and concentric phases of a given exercise, respectively. Flywheel devices provide variable resistance dependent on the amount of force developed in a given repetition. AEL can be applied during flywheel training, as force greater than that produced in the preceding concentric phase must be produced to decelerate the winding of the strap around the rotating shaft. Replicated with permission (Askling et al., 2003).

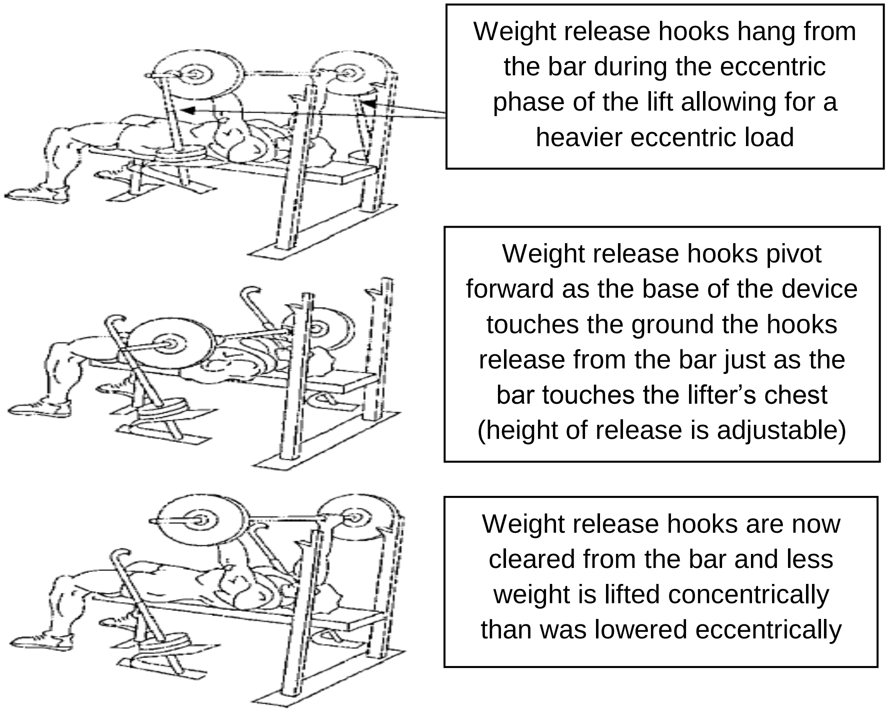
maximum to maximal isokinetic eccentric efforts. Depending on the involved population, the use of eccentric exercises with body mass alone may be employed, especially if pain upon loading is experienced (Alfredson et al., 1998). Therefore, eccentric-only resistance exercise in its numerous forms can be applied in various situations ranging from exercise physiology laboratories to field based training practices.

1.3.2 AEL

AEL involves the completion of loaded concentric and eccentric phases. However, heavier loading is employed during the eccentric phase in relation to the subsequent concentric phase (Doan et al., 2002). This type of resistance exercise attempts to equate training intensities between eccentric and concentric phases, given the greater force production capacity of eccentric muscle actions. AEL requires rapid reduction of load for the subsequent concentric phase of each repetition so as repetitions can be performed in a smooth and continuous manner. A number of systems, of varying expense and complexity, have been developed to facilitate such transitions during AEL. These systems include: (i) flywheel resistance machines (Figure 1.4); (ii) specialised variable resistance weight stack devices (Figure 1.5); (iii) automated simulated resistance machines (Figure 1.6); (iv) weight releaser hooks (Figure 1.7); and (v) manual removal of a proportion of eccentric load (Figure 1.8). Eccentric phase loads during AEL are typically at least 5.0%, heavier than the concentric phase loads implemented (Doan et al., 2002). However, the eccentric phase load used is dependent on the level of concentric loading and the type of system employed to overload the eccentric phase. Therefore, AEL can potentially be more difficult to implement than eccentric-only resistance exercise as loading, transitions between phases, and the cost of specialised AEL machinery must be considered. However, this type of eccentric-focused resistance exercise may negate the need for the completion of heavy eccentric-only resistance exercise in addition to

Figure 1.5 The MaxOut bench press machines implements a selectorised electrical motor which provides assistance during the concentric phase of the bench press and then disengages to overload the eccentric phase of the bench press. Replicated with permission (Yarrow et al., 2008).

Figure 1.6 Simulated resistance training device from IM lifter. The device permits free weight barbell training via the use of a laser sensor which moves the motorised arms on each side of the machine. This laser function safeguards the barbell without contacting the barbell during performance of a given exercise. The device also allows separate simulated loads to be programmed for the concentric and eccentric phases of a selected exercise.



Weight release hooks hang from the bar during the eccentric phase of the lift allowing for a heavier eccentric load

Weight release hooks pivot forward as the base of the device touches the ground the hooks release from the bar just as the bar touches the lifter’s chest (height of release is adjustable)

Weight release hooks are now cleared from the bar and less weight is lifted concentrically than was lowered eccentrically

Figure 1.7 Application and release of AEL weight releaser hooks during the bench press. Replicated with permission (Doan et al., 2002).

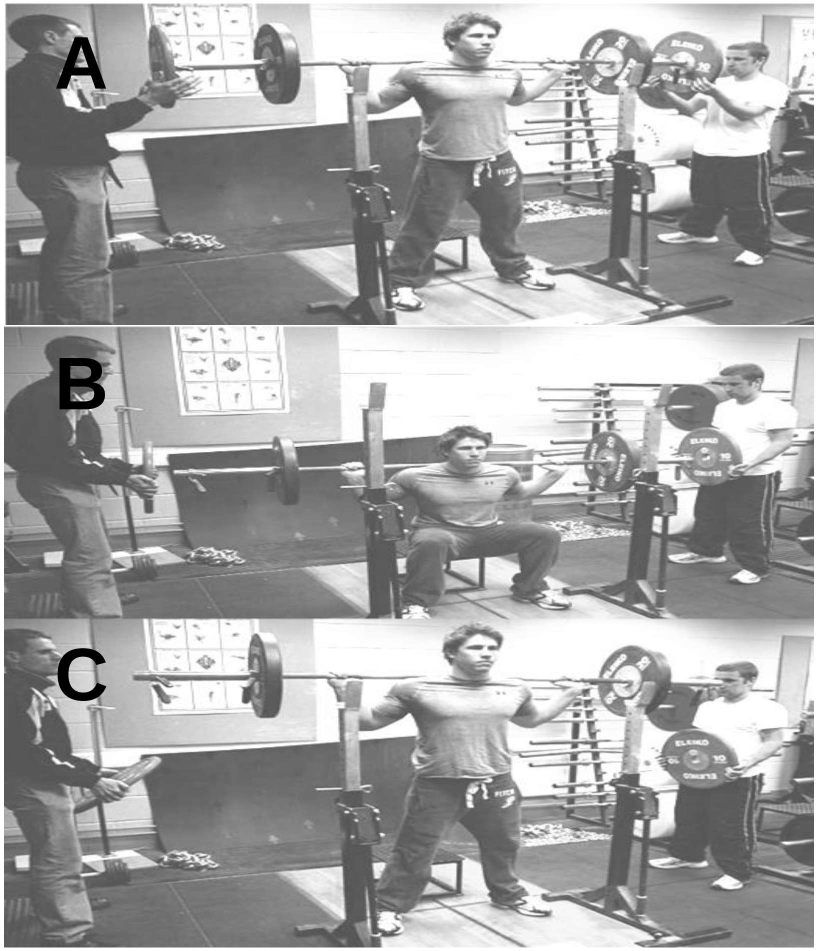


Figure 1.8 Implementation of AEL via manual application (A) and removal (B) of weight plates at either side of the barbell at the top (A) and bottom (B) of a box squat repetition. Replicated with permission (Watkins, 2010).

CL practices for individuals aiming to maximally develop both their concentric and eccentric strength.

1.4 Use of eccentric-focused resistance exercise for rehabilitation and injury prevention

1.4.1 Tendinosis rehabilitation

Chronic tendinosis is characterised by pain and degeneration of tendon tissue (Khan et al., 1999). The pathogenesis of chronic tendinosis is unclear (Fredberg and Stengaard-Pedersen, 2008). Mechanical overloading (Archambault et al., 1995), which may occur with high training volumes or with increased activity following prolonged periods of inactivity has been implicated in causing the condition. However, in a large population study of individuals with Achilles tendinosis physical activity levels were not predictive of the development of the condition (Astrom, 1998). Therefore, mechanical loading may not be causative but merely provoke tendinosis symptoms (Alfredson, 2005). The pain experienced with tendinosis can severely limit or prevent physical activity (Cook et al., 1997) and potentially shorten the duration of athletic careers (Kettunen et al., 2002). In addition, symptoms can persist after the end of an individual’s athletic career (Kettunen et al., 2002).

The use of eccentric-only resistance exercise for the management of tendinosis has typically involved progression of exercise load (Norregaard et al., 2007; Jonsson and Alfredson, 2005; Visnes et al., 2005; Roos et al., 2004; Mafi et al., 2001; Niesen-Vertommen et al., 1992), exercise velocity (Jensen and Di Fabio, 1989), or both load and velocity (Young et al., 2005). For individuals with unilateral lower body tendinosis, the injured leg is used to perform the eccentric portion of an exercise, whereas the uninjured limb performs the concentric phase (Alfredson et al., 1998). For bilateral lower-body tendinosis patients, assistance from the upper-body or a helper facilitates the participant in returning to the start of the eccentric phase of the repetition (Visnes et al., 2005). However, other studies have involved concentric muscle actions of the injured limb to return to the start of each repetition (Young et al., 2005; Silbernagel et al., 2001; Cannell et al., 2001; Niesen-Vertommen et al., 1992).

Previous research has demonstrated eccentric-only resistance exercise to reduce pain during loading (Norregaard et al., 2007; Langberg et al., 2007; Sayana and Maffulli, 2007; Jonsson and Alfredson, 2005; Young et al., 2005; Roos et al., 2004; Ohberg et al., 2004; Fahlstrom et al., 2003; Mafi et al., 2001; Silbernagel et al., 2001; Cannell et al., 2001; Alfredson et al., 1998; Niesen-Vertommen et al., 1992), improve power (Visnes et al., 2005), and increase both eccentric (Alfredson et al., 1999; Niesen-Vertommen et al., 1992) and concentric (Alfredson et al., 1999; Niesen-Vertommen et al., 1992) strength. In addition, eccentric resistance exercise has been shown to be more effective for improving strength and reducing pain compared to concentric-only resistance exercise (Jonsson and Alfredson, 2005), night splint usage (Roos et al., 2004), non-thermal ultrasound (Stasinopoulos and Stasinopoulos, 2004), and transverse friction massage (Stasinopoulos and Stasinopoulos, 2004). However, eccentric-only resistance exercise has also been reported to be equally effective for reducing pain, increasing strength, and facilitating returning to previous activity levels when compared to concentric-only resistance exercise (Mafi et al., 2001; Silbernagel et al., 2001; Cannell et al., 2001; Niesen-Vertommen et al., 1992), combined eccentric and concentric resistance exercise (Young et al., 2005), stretching (Norregaard et al., 2007), and eccentric-only resistance exercise combined with night splint usage (Roos et al., 2004). Therefore, eccentric-only resistance exercise is largely considered to be an effective form of treatment for managing chronic tendinosis (Maffulli and Longo, 2008). However, current tendinosis treatment research findings are unclear as to whether or not eccentric-only resistance exercise is superior to other types of resistance exercise (Jonsson and Alfredson, 2005), alternative treatments (Norregaard et al., 2007), or interventions combining resistance exercise and alternative treatments

(Roos et al., 2004). Furthermore, the efficacy of employing AEL for the treatment of tendinosis has not yet been determined.

The mechanistic influence of eccentric-only resistance exercise on the symptoms of tendinosis is postulated to be due to: (i) increased collagen synthesis repairing degenerated portions of the tendon; (ii) disruption of neovessel formation by upregulation of anti-angiogenic factors resulting from fluctuations in hydrostatic pressure (Shalabi et al., 2004; Alfredson and Lorentzon, 2003); (iii) enhanced eccentric phase neuromuscular control reducing forces the tendon is exposed to during loading (Baur et al., 2004); or (iv) a reduction in the concentration of substances (glutamate, calcitonin gene related peptide, and substance P) associated with the symptomatic pain experienced with tendinosis (Alfredson and Lorentzon, 2003). In particular, the latter two mechanisms have received minimal attention. Studies have noted differences in eccentric neuromuscular activation of the lower leg musculature during running (Baur et al., 2004) and heel drop exercises (Reid et al., 2012) when comparing individuals with and without chronic tendinosis. However, synchronous neuromuscular measures during kinetic and kinematic assessments of gait, jumping, or running have not been incorporated within existing tendinosis training intervention research. Therefore, the potential role of neuromuscular adaptation in the treatment and management of tendinosis remains unclear. Glutamate levels have been shown to be unchanged following an eccentric-only resistance exercise training intervention (Alfredson and Lorentzon, 2003). It was consequently speculated that eccentric-only resistance exercise, which can be painful in individuals with tendinosis, may desensitise glutamate receptors. Decreased receptor sensitivity would explain the reported return to previous activity levels and reduction of pain, without a concomitant reduction in glutamate levels (Alfredson and Lorentzon, 2003). However, whether or not changes in other substances (calcitonin gene related peptide and substance P) implicated in symptomatic tendinosis pain (Fredberg and Stengaard-Pedersen, 2008) occur, and how these alterations may influence strength and pain following eccentric-only resistance exercise have not yet been investigated. Therefore, future research investigating neuromuscular control adaptations, calcitonin gene related peptide and substance P concentrations following eccentric-only resistance exercise in tendinosis patients seems warranted. Such research would further current understanding of how eccentric-only resistance exercise influences strength and pain in tendinosis patients.

1.4.2 Anterior cruciate ligament rehabilitation

Anterior cruciate ligament injury occurs commonly in a range of sports (Agel et al., 2005; Myklebust et al., 2003; Roos et al., 1995). Large strength losses can occur after anterior cruciate ligament surgery (Feller and Webster, 2003; Meighan et al., 2003; Arangio et al., 1997). In addition, anterior cruciate ligament injury can often lead to decreases in sporting career duration (Mikkelsen et al., 2000; Gerich et al., 1997; Roos et al., 1995; Noyes et al., 1983) and the level of competitive sports participation (Ejerhed et al., 2003). Resistance exercise forms an integral component of post-anterior cruciate ligament surgery rehabilitation and quadriceps muscle strength has been associated with positive outcomes following anterior cruciate ligament surgery (Wojtys and Huston, 2000; Risberg et al., 1999; Wilk et al., 1994). Research examining optimal resistance exercise protocols has manipulated numerous variables to determine the most effective anterior cruciate ligament rehabilitation programmes. Investigated anterior cruciate ligament rehabilitation programme variables have included: (i) kinetic chain exercise type (Hooper et al., 2001; Mikkelsen et al., 2000; Bynum et al., 1995); (ii) rate of exercise progression (Beynnon et al., 2005; Shelbourne and Trumper, 1997; Shelbourne and Nitz, 1990; Noyes et al., 1987); (iii) the amount of time post-surgery when full range of movement is permitted (Noyes et al., 1987); and (iv) the type of muscle actions included (Gerber et al., 2009; Gerber et al., 2007b; Gerber et al., 2006; Coury et al., 2006).

The potential importance of eccentric-focused resistance exercise for anterior cruciate ligament patients was identified following observations of deficient movement strategies during gait and eccentric strength deficits in this population (Lastayo et al., 2003a). However, to date only a limited number of studies have investigated the use of eccentric-only resistance exercise for rehabilitation following anterior cruciate ligament injury (Gerber et al., 2009; Gerber et al., 2007b; Gerber et al., 2006). Both eccentric isokinetic dynamometry and eccentric ergometers have been employed in these studies. Current findings have shown the completion of eccentric-only resistance exercise during anterior cruciate ligament rehabilitation to increase concentric strength (Gerber et al., 2009; Gerber et al., 2007b; Gerber et al., 2006), eccentric strength (Coury et al., 2006), and single-leg jumping distance (Gerber et al., 2009; Gerber et al., 2007b) compared to pre-surgery or pre-training intervention measures. Eccentric-only resistance exercise has also been shown to be successful in facilitating patient's return to pre-injury activity levels (Gerber et al., 2009; Gerber et al., 2006). In addition, equivalent traditional rehabilitation programmes including concentric resistance exercise did not result in the same improvements in strength and single-leg jump distance as eccentric-only resistance exercise rehabilitation regimes (Gerber et al., 2009; Gerber et al., 2007b).

The reported benefits of eccentric-only resistance exercise anterior cruciate ligament rehabilitation have been attributed to increases in muscle and connective tissue stiffness (Coury et al., 2006). The higher force levels involved in eccentric-only resistance exercise anterior cruciate ligament rehabilitation are believed to be responsible for the greater increases in strength and muscle mass (Gerber et al., 2007b), compared to those seen with equivalent concentric programmes. The positive results reported from the limited research literature following eccentric-only compared to concentric-only resistance exercise or traditional anterior cruciate ligament rehabilitation suggest that eccentric-only resistance exercise anterior cruciate ligament rehabilitation is more effective, whilst also being safe and well tolerated by patients (Gerber et al., 2007b). The use of AEL during anterior cruciate ligament rehabilitation has not yet been investigated. It may be expected that AEL would produce similar anterior cruciate ligament rehabilitation benefits to eccentric-only resistance exercise, given the high levels of eccentric force that are also involved in this type of training. However, studies investigating AEL compared to other types of resistance exercise employed during anterior cruciate ligament rehabilitation are required to investigate: (i) whether or not AEL is more or less effective in comparison to existing rehabilitation practices; (ii) if AEL can be safely implemented with anterior cruciate ligament rehabilitation patients; and (iii) if this type of resistance exercise is tolerable for anterior cruciate ligament rehabilitation patients.

1.4.3 Hamstring muscle strain injury prevention

Research investigating the use of eccentric-focused resistance exercise in the prevention of muscle strain injuries has focused predominantly on the hamstring muscle group (Petersen et al., 2011; Arnason et al., 2008; Gabbe et al., 2006; Brooks et al., 2006). The high rates of hamstring injury reported in sprinting and team sports make both injury prevention and reduction of reinjury areas which can have considerable benefits for competitive performance and career duration (Mjolsnes et al., 2004). Both eccentric-only resistance exercise (Petersen et al., 2011; Arnason et al., 2008; Gabbe et al., 2006; Brooks et al., 2006) and AEL (Askling et al., 2003) have been employed in hamstring injury prevention intervention studies. Eccentric-only resistance exercise has been implemented via the Nordic hamstring exercise (Petersen et al., 2011; Arnason et al., 2008; Gabbe et al., 2006; Brooks et al., 2006) (Figure 1.2) and isokinetic dynamometry (Croisier et al., 2002). AEL has been implemented using a knee curl flywheel device (Askling et al., 2003). Eccentric-focused resistance exercise is believed to prevent injuries by increasing eccentric strength (Mjolsnes et al., 2004) and shifting the angle of peak eccentric force to longer muscle lengths (Brockett et al., 2001). Both of these adaptations are believed to protect the hamstrings and therefore reduce the incidence of injuries to this muscle group.

Interventions implementing the Nordic hamstring exercise have reduced the incidence of hamstring injury (Petersen et al., 2011; Arnason et al., 2008) and decreased the severity of hamstring injury with regard to the distribution of injuries (Arnason et al., 2008). Eccentric-only resistance exercise implemented via isokinetic dynamometry has also been shown to be effective in preventing hamstring injury occurrence (Queiros Da Silva et al., 2005; Croisier et al., 2002). Similarly, AEL injury prevention interventions have demonstrated decreased hamstring injury rates and improved strength and power (Askling et al., 2003). In contrast, other findings suggest Nordic hamstring exercise training interventions do not reduce the incidence of injury (Engebretsen et al., 2008; Gabbe et al., 2006) or the prevalence of injury reoccurrence (Arnason et al., 2008). The equivocal findings from the eccentric-only resistance exercise research in this area are likely due to differences in training volume (Gabbe et al., 2006) and programme adherence (Engebretsen et al., 2008; Gabbe et al., 2006). The only AEL hamstring injury prevention study conducted demonstrates the potential of this training method to reduce injury rates (Askling et al., 2003).

Previously, a rehabilitation intervention progressing from isometric to combined concentric and eccentric resistance exercise has displayed high hamstring injury reoccurrence rates at short- and long-term follow-up time-points (Sherry and Best, 2004). This may potentially be due to the daily training frequency employed in this study compared to other hamstring injury prevention studies or the resistance exercise regime employed. Indeed, eccentric-only resistance exercise has been shown to increase eccentric strength compared to combined eccentric and concentric resistance exercise (Mjolsnes et al., 2004). The high rate of injury reoccurrence (Sherry and Best, 2004) and lack of improvement in eccentric strength (Mjolsnes et al., 2004) following combined eccentric and concentric resistance exercise training interventions suggests eccentric-focused resistance exercise may be a superior injury prevention strategy.

The finding that combined eccentric and concentric resistance exercise failed to increase eccentric strength may mean this type of training was also insufficient to cause an increase in the muscle length at which peak eccentric force occurs (Mjolsnes et al., 2004; Brockett et al., 2001). Therefore, combined eccentric and concentric resistance exercise may not have influenced either of the postulated mechanisms that are belived to be responsible for reduced hamstring injury rates following eccentric-focused resistance exercise. However, limited direct comparisons have been made between eccentric-focused resistance exercise and other types of resistance exercise for the purposes of hamstring injury prevention. One study has reported the addition of eccentric–only resistance exercise to a combined eccentric and concentric resistance exercise and stretching programme to reduce the incidence of hamstring injury, compared to a group completing only combined eccentric and concentric resistance exercise (Brooks et al., 2006). Elsewhere, no differences have been reported in the occurrence of hamstring injury when eccentric-only, concentric-only, and combined eccentric and concentric resistance exercise have been employed (Croisier et al., 2002). Therefore, further research is required to elucidate whether eccentric-focused resistance exercise is more effective in reducing the incidence of hamstring injuries compared to other types of resistance exercise.

1.4.4 Fall incidence reduction

The risk of falling at least once a year increases with age for adults aged 65 or older (Stalenhoef et al., 1997; Downton and Andrews, 1991; Blake et al., 1988; Tinetti et al., 1988; Campbell et al., 1981; Prudham and Evans, 1981). Falls have previously been identified as the leading cause of accidental death in older adults, a high proportion of these falls occur on stairs (Cavanagh et al., 1997). When falls do not prove to be fatal, hip fractures are often sustained (Parkkari et al., 1999; Grisso et al., 1991) which can lead to disability and functional impairment (Carter et al., 2001). Step frequency in older adult populations during stair descent appears to be greater than ascent at a self-selected velocity (Larsen et al., 2008) and fall frequency is at least three times greater during stair descent, compared to ascent (Startzell et al., 2000). Therefore, suggesting eccentric muscle action characteristics are implicated in the incidence of falls. This seems particularly likely given the importance of eccentric muscle actions during stair descents (Lastayo et al., 2003b; McFadyen and Winter, 1988; Andriacchi et al., 1980). Indeed, the ability to produce precise changes in eccentric force deteriorates more than concentric force with age (Hortobagyi et al., 2001b; Enoka, 1997). The decrease in force steadiness with ageing is attributed to increases in motor unit firing rate variance (Laidlaw et al., 1999).

Previously, combined eccentric and concentric resistance exercise has been shown to reduce eccentric force error in older adults (Hortobagyi et al., 2001b; Laidlaw et al., 1999). Furthermore, a number of studies employing combined eccentric and concentric resistance exercise have reduced the incidence of falls in older adult populations compared to control groups (Rubenstein et al., 2000; Campbell et al., 1999; Campbell et al., 1997; Buchner et al., 1997). Therefore, combined eccentric and concentric resistance exercise appears to be an effective intervention in reducing the incidence of falls. However, the efficacy of using AEL or eccentric-only resistance exercise for reducing the incidence of falls compared to other types of resistance exercise has not yet been investigated. If found to be equally or more effective than combined eccentric and concentric resistance exercise for preventing the incidence of falls, eccentric-focused resistance exercise models may provide a training model that is both an effective and energy efficient exercise model for exercise-intolerant older adults (Lastayo et al., 2003a). Therefore, future research investigating the benefits of AEL and eccentric-only resistance exercise for reducing the incidence of falls, would help further inform exercise prescription for older adult populations identified as being at risk of falling.

1.5 Use of eccentric-focused resistance exercise for functional performance

1.5.1 Enhancement of strength

Eccentric-only resistance exercise

Strength adaptations following resistance exercise are important for both young and older adults. Strength levels have been demonstrated to be correlated with sprinting and jumping performance in athletic populations (Wisloff et al., 2004). Additionally, lower limb strength has been associated with the frequency of falls in older adults (Lord et al., 1995). Therefore, strength development is essential for both athletic and older adult populations.

Numerous studies have examined strength gains following eccentric-only *vs.* concentric-only resistance exercise in healthy young participants (Moore et al., 2012; Vikne et al., 2006; Hortobagyi et al., 1996b; Komi and Buskirk, 1972). Eccentric-only resistance exercise has been shown to increase eccentric (Mjolsnes et al., 2004; Farthing and Chilibeck, 2003a; Higbie et al., 1996; Hortobagyi et al., 1996a; Hortobagyi et al., 1996b; Tomberlin et al., 1991; Duncan et al., 1989; Komi and Buskirk, 1972), concentric (Farthing and Chilibeck, 2003a; Komi and Buskirk, 1972), and isometric strength (Mjolsnes et al., 2004; Lastayo et al., 1999; Hortobagyi et al., 1996a; Komi and Buskirk, 1972). Equally, concentric-only resistance exercise has been shown to increase eccentric (Moore et al., 2012; Vikne et al., 2006; Seger et al., 1998; Tomberlin et al., 1991), concentric (Higbie et al., 1996; Hortobagyi et al., 1996a; Hortobagyi et al., 1996b; Duncan et al., 1989), and isometric (Moore et al., 2012; Hortobagyi et al., 2000; Seger et al., 1998; Hortobagyi et al., 1996a) strength. Eccentric strength adaptations have been demonstrated to be greater following eccentric-only resistance exercise training interventions compared to concentric-only resistance exercise (Vikne et al., 2006; Mjolsnes et al., 2004; Higbie et al., 1996). In addition, similar concentric strength gains have been displayed following eccentric-only and concentric-only resistance exercise training interventions (Vikne et al., 2006; Hortobagyi et al., 2000). In contrast, other studies suggest that strength adaptations are mode specific for eccentric-only and concentric-only resistance exercise (Higbie et al., 1996; Hortobagyi et al., 1996a; Hortobagyi et al., 1996b; Duncan et al., 1989; Komi and Buskirk, 1972). For example, eccentric-only resistance exercise stimulates greater or exclusive increases in eccentric compared to concentric strength. Therefore, it remains unclear if employing eccentric-only resistance exercise consistently leads to improvements in both concentric and eccentric strength.

Previous research has reported the effectiveness of combined eccentric and concentric resistance exercise with healthy older adults for increasing concentric strength (see reviews (Reeves et al., 2006; Macaluso and De, 2004)). However, compared to the eccentric-only resistance exercise research conducted with young healthy participants, limited research has explored the use of this type of resistance exercise with older adults (Reeves et al., 2009; Lastayo et al., 2003a). Eccentric-only resistance exercise has been shown to lead to muscle action specific increases in strength in older adults, with no change in the strength levels of the opposing concentric muscle action (Reeves et al., 2009). The use of eccentric-only resistance exercise with older adults has been advocated as absolute eccentric strength is better maintained than concentric strength in this population (Roig et al., 2010). Furthermore, the high force levels and low energy cost of eccentric muscle actions have been suggested to provide the required levels of mechanical stress for strength and muscle mass gains for exercise-intolerant older individuals (Lastayo et al., 2003a). Further studies are required to substantiate the efficacy of using eccentric-only resistance exercise for improving both strength and related mobility performance in older adult populations.

AEL

Several studies have investigated the effectiveness of AEL for improving strength and power compared to CL. Enhanced concentric power (Friedmann-Bette et al., 2010; Sheppard et al., 2008a), concentric (Brandenburg and Docherty, 2002; Hortobagyi and Devita, 2000; Nichols et al., 1995), eccentric (Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000), and isometric (Norrbrand et al., 2008; Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000) strength have been reported in both young and older adults following AEL. Elsewhere, no differences in strength adaptations have been reported in AEL *vs.* CL training studies (Friedmann-Bette et al., 2010; Yarrow et al., 2008; Godard et al., 1998; Ben-Sira et al., 1995). The greater chronic strength gains with AEL have been attributed to both neuromuscular (Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000) and morphological (Norrbrand et al., 2008; Friedmann et al., 2004) adaptations. In contrast, other longer duration AEL training intervention studies have not reported morphological changes in either CL or AEL conditions, despite greater chronic strength adaptations occurring with AEL (Norrbrand et al., 2008; Brandenburg and Docherty, 2002). Therefore, neuromuscular adaptations seem to be a crucial factor in the superior strength and power improvements reported with AEL. However, besides two AEL studies of short duration (7 d) employing intensified training, no measures of neuromuscular adaptation have been performed during longer duration AEL interventions.

Acute AEL studies have also been conducted as a result of speculation that chronic enhancements in strength and power reported with AEL occur due to elevated acute concentric kinetic and kinematic responses within individual training sessions, that make up the overall intervention (Sheppard and Young, 2010; Ojasto and Hakkinen, 2009a; Sheppard et al., 2007; Doan et al., 2002). Increased neural stimulation, recovery of elastic energy, greater contractile filament overlap, and amplified development of tension in the eccentric phase have been theorised to be responsible for the larger acute concentric kinetic and kinematic outputs observed with

AEL (Doan et al., 2002). To date, only a single acute upper-body study has synchronously measured neuromuscular, kinetic, and kinematic variables (Ojasto and Hakkinen, 2009a). In this study, no elevation in concentric neuromuscular activation occurred, despite an enhancement in concentric peak and mean power occurring in the AEL condition (Ojasto and Hakkinen, 2009a). Furthermore, acute lower limb studies comparing AEL to CL have not included neuromuscular measures (Moore et al., 2007; Sheppard et al., 2007). Therefore, whether or not differential acute neuromuscular responses occur either during or after lower limb AEL is uncertain. Although, enhanced chronic strength adaptations have been reported following AEL, the mechanistic rationale for employing this type of resistance exercise is far from conclusive. Further research employing a spectrum of neuromuscular measures may elucidate differential acute demands and physiological responses that may be implicated in the enhanced chronic strength gains that have been observed with AEL.

1.5.2 Enhancement of mobility and activities of daily living

Quality of life is considered to be influenced, in part, by an individual’s mobility (Campanelli, 1996). Losses of strength and muscle mass occur in a range of conditions (Scott et al., 2011; Bhasin et al., 2000; Hurley, 1995; Stelmach et al., 1989) and can lead to reduced functional mobility and impairments in the ability to perform other activities of daily living. Decreased mobility levels and the inability to perform activities of daily living often leads to institutionalisation and can severely impact quality of life (Campanelli, 1996), whilst also leading to a variety of health and residential care costs (Paterson and Warburton, 2010).

The effectiveness of eccentric-only resistance exercise for improving functional mobility has been investigated in a range of populations with conditions predisposing these individuals to strength and muscle mass losses

(Lastayo et al., 2011; Lastayo et al., 2010; Dibble et al., 2009; Lastayo et al., 2009; Hansen et al., 2009; Mueller et al., 2009; Marcus et al., 2009; Dibble et al., 2006; Lastayo et al., 2003a). Such studies have employed specialised recumbent eccentric ergometers that allow progressive increases in loading (Meyer et al., 2003). Improvements in 6 min walk (Dibble et al., 2006), 10 m walk (Dibble et al., 2009), timed up and go (Dibble et al., 2009; Lastayo et al., 2003a), stair ascent (Lastayo et al., 2009), and stair descent (Lastayo et al., 2010; Lastayo et al., 2009; Lastayo et al., 2003a) performance have been reported from pre- to post-intervention with eccentric ergometry training. Furthermore, the improvements in 6 min walk (Lastayo et al., 2011; Dibble et al., 2006), 10 m walk (Dibble et al., 2009), balance (Lastayo et al., 2003a), and stair descent (Dibble et al., 2009; Lastayo et al., 2009; Lastayo et al., 2003a) following eccentric ergometry have been reported to be greater than those following combined eccentric and concentric resistance exercise (Dibble et al., 2009; Lastayo et al., 2009; Dibble et al., 2006; Lastayo et al., 2003a) or usual care programmes (Lastayo et al., 2011). In contrast, improvements in timed up and go (Lastayo et al., 2009; Mueller et al., 2009) and stair ascent (Lastayo et al., 2009) performance after eccentric ergometry exercise have not been found to be greater than those reported with combined eccentric and concentric resistance exercise. The lack of differences reported between eccentric-only and combined eccentric and concentric resistance exercise interventions in the stair ascent and timed up and go tasks is perhaps due to the predominant role of concentric muscle actions, or the brevity of these tests, respectively. Tasks with a greater eccentric component such as the stair descent and 6 min walk test appear to respond more positively to eccentric-only resistance exercise compared to combined eccentric and concentric resistance exercise in the populations that have been investigated. Only one study has examined changes in functional task performance (stair ascent, balance, shelf task, and bag carry) in an older adult population following AEL (Nichols et al., 1995). However, the functional task results of the AEL and CL training groups in this study were combined and then compared to a non-exercising control group (Nichols et al., 1995). Therefore, based on the results presented it was not possible to determine if AEL improved functional task performance more than CL.

Individuals from populations who characteristically experience muscle atrophy appear to improve functional mobility in tasks that have a dominant eccentric component following eccentric resistance exercise. The effectiveness of AEL and eccentric-only resistance exercise for a range of other disease populations has yet to be investigated. The performance of mobility tasks in individuals with other conditions who experience muscle atrophy (e.g. acquired immunodeficiency syndrome, multiple sclerosis, muscle dystrophy, and Guillain-Barré syndrome) following eccentric-focused resistance exercise has not been examined. The comparison of eccentric-focused resistance exercise to other types of resistance exercise would provide essential information that would inform exercise prescription for these populations and potentially contribute to the maintainance or improvement of mobility.

1.6 Conclusions and implications from the literature review

Both AEL and eccentric-only resistance exercise have a range of uses in rehabilitation, injury prevention, and functional performance enhancement. Therefore, these two types of eccentric-focused resistance exercise have application to a large range of different populations, from athletes to individuals who have conditions where muscle atrophy occurs. The existing research investigating these two types of eccentric-focused resistance exercise has informed the exercise prescription of practitioners who work with these diverse populations. A number of future research projects that would add to the existing eccentric-focused resistance exercise literature have been identified in this chapter. In particular, the use of AEL for the development of chronic strength and power adaptations remains a controversial topic, given the contrasting research findings and general lack of neuromuscular measures in the existing research in this area. This controversy is compounded by the number of interacting variables inherent in longitudinal training intervention research studies. Research investigating acute neuromuscular responses to lower-body AEL in comparison to CL may provide practitioners with information that would guide their decision to use this type of resistance exercise. In addition, this line of research would determine how AEL influences neuromuscular variables, such as motor unit firing rate and common drive, that may be implicated in chronic strength adaptations.

1.7 Aims of the thesis

In order to investigate acute neuromuscular responses during lower-body multiple-joint free weight AEL compared to CL it was deemed important to: (i) evaluate potential surface electromyography (EMG) normalisation methods; and (ii) investigate the reliability of motor unit firing rates during lower-body isometric efforts. Therefore, there were two methodological aims of this thesis:

- To evaluate the reliability of maximal isometric (both with and without the use of a dynamometer) and submaximal dynamic normalisation methods for concentric and eccentric phase EMG during the back squat exercise.
- To establish the reliability of motor unit firing rate determined from high density EMG during an isometric trapezoid force trace effort.

The main aims of the thesis were:

- To examine differences in acute neuromuscular, kinetic, and kinematic responses between AEL and CL conditions during:
    (i) Lower-body single-joint resistance exercise.
    (ii) Lower-body multiple-joint free weight resistance exercise.
- To assess acute force production and contractile characteristics following AEL and CL conditions.

- To investigate the influence of eccentric phase velocity (and time under tension) on acute force production, power output, and contractile characteristics following AEL and CL conditions.
- To compare common drive and motor unit firing rate responses after AEL and CL.

CHAPTER 2

EVALUATION OF ELECTROMYOGRAPHY NORMALISATION METHODS FOR THE BACK SQUAT

Balshaw TG, Hunter AM.

2.1 Introduction

Before comparing neuromuscular responses during lower-body multiple-joint free weight AEL and CL it was deemed necessary to: (i) select a lower-body resistance exercise that had application for use by both athletic and general populations; and (ii) establish an appropriate surface EMG normalisation method for the selected resistance exercise. The free weight barbell back squat was selected as the lower-body resistance exercise to be investigated as a result of its widespread use amongst athletic populations and its inclusion within position statements on progressive resistance exercise for the general population (Ratamess et al., 2009). The back squat is a staple multiple-joint free weight resistance exercise that can be used to increase the strength of knee and hip extensor muscles such as the vastus lateralis and biceps femoris. Increasing the force production capabilities of these muscles can often translate into improvements in performance of one or several athletic skills (Channell and Barfield, 2008; Myer et al., 2005), such as sprinting, jumping, throwing, or striking.

Normalisation, the practice of reporting EMG data as a percentage of that achieved during a controlled reference task is a prerequisite for reducing intrinsic and extrinsic factors that contribute to signal variation (Lehman and McGill, 1999). Normalisation methods allow for comparison of neuromuscular activation between different muscles, participants, and studies (Mathiassen et al., 1995; Knutson et al., 1994). Existing research has evaluated normalisation methods for dynamic single-joint upper-body resistance exercise (Burden and Bartlett, 1999; Allison et al., 1993), but not multiple-joint lower-body resistance exercise. Dynamometer-based maximal voluntary isometric muscle actions (MVC) have previously been recommended for EMG normalisation across different activities (Merletti, 1999). However, the incorporation of the MVC normalisation method into research examining neuromuscular activation during dynamic muscle actions has been questioned for several reasons (Albertus-Kajee et al., 2010; Nishijima et al., 2010; Farina et al., 2004; Hunter et al., 2002; Clarys, 2000; Allison et al., 1993; Yang and Winter, 1983). Such issues include: (i) muscle fibre shifting beyond the electrode detection area (Albertus-Kajee et al., 2010; Farina et al., 2002); (ii) conclusions regarding absolute neuromuscular activation (Albertus-Kajee et al., 2010; Clarys, 2000); (iii) motivational issues (Burden, 2010); and (iv) the disparity between muscle action, load, and velocity of the MVC normalisation task and the dynamic activity being investigated (Allison et al., 1993). Moreover, MVC normalisation requires specialized equipment and additional data collection time (Nishijima et al., 2010), which places further demands on the researcher and participant sample.

Irrespective of exercise activity, existing research has investigated the use of different intensity efforts and muscle action types for normalisation. Several studies have demonstrated that submaximal isometric (Mathur et al., 2005; Kollmitzer et al., 1999; Yang and Winter, 1983) and maximal dynamic normalisation methods (Ball and Scurr, 2010; Rouffet and Hautier, 2008; Mathur et al., 2005), can provide viable alternatives to MVC normalisation for upper (Yang and Winter, 1983) and lower limb (Ball and Scurr, 2010; Rouffet and Hautier, 2008; Mathur et al., 2005; Kollmitzer et al.,

1999) muscles. Only two studies have evaluated the between-day reliability of submaximal dynamic normalisation protocols (for cycling (Albertus-Kajee et al., 2010) and running (Albertus-Kajee et al., 2011)). Therefore, the evaluation of EMG normalisation methods for the back squat will allow neuromuscular responses to AEL and CL to be compared for this specific exercise.

The purpose of the present study was threefold: firstly, to evaluate the reliability of maximal isometric (both with and without a dynamometer) and submaximal dynamic normalisation methods for concentric and eccentric phase neuromuscular activity during the back squat exercise; secondly, to examine the sensitivity of each method in detecting statistical differences between neuromuscular activity levels in incremental intensity dynamic back squat exercise sets, as recently conducted in normalisation research for other exercise modes (Albertus-Kajee et al., 2011; Albertus-Kajee et al., 2010); thirdly, to assess differences in neuromuscular activation between strength-trained individuals during the back squat. The measurement of inter-participant variability was included because it had not previously been detailed for strength-trained individuals performing the back squat exercise.

2.2 Methods

2.2.1 Participants

Ten males (aged: 24.4 ± 6.9 years, body mass: 82.0 ± 9.6 kg, height: 1.76 ± 0.04 m, sum of seven skin folds: 69.8 ± 40.3 mm, mean ± standard deviation (SD)), with a minimum of 2 years' of experience of performing the back squat exercise (relative three repetition maximum (3RM) strength: 1.7 ± 0.2 times body mass, absolute 3RM back squat bar load: 139.0 ± 20.1 kg) were recruited to participate in the study. Informed consent was obtained from each participant before testing commenced, following approval of the investigation from the University of Stirling Research Ethics Committee. The study was conducted in accordance with the principles outlined in the

Declaration of Helsinki (2008). Participants completed test sessions at the same time of day to account for circadian variation (Atkinson and Nevill, 1998). In addition, participants avoided exhaustive exercise in the 24 h prior to each test session and maintained usual dietary habits.

2.2.2 Procedures

Baseline assessment test session: 3RM strength test and familiarisation

The first session of four conducted within the investigation involved the establishment of back squat 3RM. The remaining three subsequent test day sessions allowed the evaluation of reliability, sensitivity, and inter-participant variability of each normalisation method. Prior to the 3RM assessment participants were provided with a predicted 3RM based on estimated one repetition maximum (one repetition maximum load (kg) x 0.92), in order to guide load selection (Baker, 1995). Participants selected load and repetition number for the four warm-up sets in an incremental manner to prepare for four attempts at establishing 3RM to the nearest 2.5 kg (Eleiko Sport, Halmstad, Sweden). After the warm-up sets, recovery between 3RM attempts was standardised at 3 min (Harman and Garhammer, 2008).

Squat stance width was selected by the participant prior to the 3RM warm-up sets and this was marked on the lifting surface to control stance width and position within the squat rack during all testing sessions. A flexible two-dimensional electrogoniometer (TSD130B, Biopac Systems Inc, California, USA) was attached to the participant’s dominant leg during all test day sessions to ensure sufficient dynamic back squat depth (Caterisano et al., 2002). In addition, forward lean of the torso during all dynamic back squats was visually checked, to ensure it was not excessive (Caterisano et al., 2002). The average duration of the concentric and eccentric phases during the heaviest successful 3RM attempt and back squats during subsequent test sessions was determined by measuring barbell displacement via a linear transducer (Celesco PT5A-125-S47-UP-10K-M6, Chatsworth, California, USA). This allowed the prescription of individualised dynamic back squat velocities in the subsequent test day sessions. The concentric and eccentric phase durations across dynamic back squat normalisation tasks and the investigated activity dynamic back squat sets during subsequent test sessions were 1.32 ± 0.01 s and 1.41 ± 0.02 s, respectively (mean ± SD)). Following the 3RM attempts participants completed familiarisation tasks in order to prepare for the subsequent test day sessions.

Participants were familiarised with the execution of controlled velocity squats. Participants completed as many squats with an unloaded barbell as necessary to become accustomed to meeting audible tones produced from a custom-built metronome, signalling the start of the eccentric and concentric phases of the back squat. A 2 s inter-tone duration for each back squat phase was used for familiarisation purposes. Isometric back squat familiarisation was also completed, directly after metronome habituation. The barbell was fastened to a squat rack at a height permitting 70° of knee flexion (0° equalling full knee extension) to allow isometric squats to be performed. A 70° knee flexion angle was selected as this amount of flexion has previously been shown to correspond with peak isometric force production (Knapik et al., 1983).

Loading determined from 3RM for subsequent test day sessions

The sum of the barbell load for the heaviest successful 3RM attempt and 88.6% of body mass were used to establish 3RM back squat system mass (Brandon et al., 2011). This percentage of body mass was used in the calculation of system mass as the foot and shank are not moved vertically during the back squat (Dugan et al., 2004; de Leva, 1996). Barbell load was adjusted accordingly for each subsequent test day session, in order to equate system mass load for dynamic back squat normalisation tasks and dynamic back squat exercise sets across sessions.

2.2.3 Experimental protocol

Subsequent test day sessions

The three subsequent test day sessions following the baseline strength test session day commenced with the completion of five different normalisation tasks (Figure 2.1). The five normalisation tasks were as follows: (i) a seated dynamometer-based isometric MVC; (ii) a maximal isometric back squat (MIS); (iii) a 60% of 3RM back squat set; (iv) a 70% of 3RM back squat set; and (v) an 80% of 3RM back squat set. Loads of 60%, 70%, and 80% of 3RM where selected for the submaximal dynamic normalisation tasks in accordance with recommendations to perform incremental intensity lifts before heavy resistance exercise (Harman and Garhammer, 2008). Therefore, the evaluation of normalisation tasks corresponding to a warm-up before the exercise of interest could potentially remove the need for additional unrelated tasks used for normalisation such as MVC. Time between test days was 8.70 ± 0.62 d (mean ± SD).

MVC normalisation task. The first normalisation task within the subsequent test day sessions was a 5 s dynamometer-based knee extension MVC. Three MVCs were performed with the participant’s dominant leg at 70° of knee flexion (0° equalling full extension; Biodex 3 dynamometer, Biodex Medical Systems, Shirley, New York, USA; Figure 2.2). The 70° knee joint flexion position allowed knee joint angles to be equated between MVC and MIS normalisation tasks. One min recovery periods separated every maximal isometric effort. During MVCs participants were firmly restrained at the shoulders, waist, and non-dominant leg to minimise extraneous bodily movements. Dynamometer axis, seat, and attachment settings were standardised across trial days for each participant. The lateral femoral epicondyle was positioned in line with the dynamometer axis and the dynamometer attachment strap was positioned above the lateral malleolus. The instruction to produce maximal force as quickly as possible from the start signal was given prior to all maximal isometric efforts on each

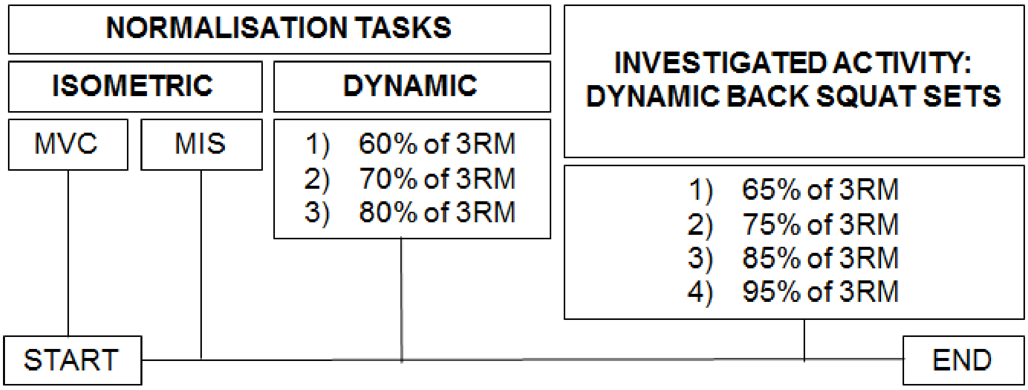


Figure 2.1 Experimental protocol for an individual test day session. Dynamic normalisation method and dynamic back squat exercise set intensities are percentages of a 3RM strength test.

test session day. Participants were also instructed to maintain force as evenly as possible once maximum force had been reached. A computer monitor displaying the MVC force trace was placed in front of participants at eye-level to assist participants in maintaining force levels after peak force had been attained. Participants received intense verbal encouragement during all maximal isometric efforts (Campenella et al., 2000). Prior to the MVC efforts participants completed a standardised warm-up (six 5 s isometric efforts (three at 50% and three at 75% of perceived maximum), with 30 s recovery periods). MVCs were followed (in randomised order) by the remaining normalisation tasks.

MIS normalisation task. Three 5 s maximal isometric back squats (MISs) were performed on a force platform (400 series force platform, Fitness Technology, Adelaide, Australia), with the barbell secured to the frame of the force platform squat rack at a height permitting 70° of knee flexion. Three 5 s isometric back squat warm-up efforts at 75% of perceived maximum were conducted prior to the MIS efforts. Participants were instructed to maintain force as evenly as possible during MISs once maximum force had been reached. It is important to note that hip flexion did differ between the isometric normalisation tasks as the MIS was performed in an upright position whereas the MVC was performed with participants seated.

Figure 2.2 Biodex 3 dynamometer.

60%, 70%, and 80% of 3RM normalisation tasks. Three different dynamic back squat normalisation tasks were conducted. A range of different dynamic back squat normalisation task intensities were used, based on the recent assertion that differences may exist between submaximal dynamic normalisation tasks (Albertus-Kajee et al., 2010). Five dynamic back squat repetitions were completed in each different intensity normalisation task set. The dynamic back squat normalisation task sets were conducted in the following order: (i) 60% of 3RM; (ii) 70% of 3RM; and (iii) 80% of 3RM. Three min recovery periods between submaximal intensity warm-up squat sets were used.

Performance of the investigated exercise activity: dynamic back squat exercise sets. Once all five normalisation tasks were completed, each of the three subsequent test day sessions concluded with four sets of different intensity dynamic back squats. Three min recovery intervals were used between dynamic back squat exercise sets

Each dynamic back squat set consisted of three repetitions at the following intensities: (i) 65% of 3RM; (ii) 75% of 3RM; (iii) 85% of 3RM; and (iv) 95% of 3RM.

2.2.4 EMG

EMG data collection

Vastus lateralis and biceps femoris EMG were recorded (Biopac MP100, Biopac Systems Inc, California, USA) from the dominant leg during all test activities during the three subsequent test day sessions. Skin preparation involved removal of hair, cleansing of the skin with alcohol swabs, and abrasion with emery paper. A reference electrode secured with micropore tape was positioned on the patella of the participant's dominant leg. A bipolar electrode configuration (VERMED A10005-60 performance plus ECG diagnostic electrodes, Vermont, USA) was applied to the vastus lateralis and biceps femoris in accordance with the surface EMG for the non-invasive assessment of muscles guidelines (Hermens et al., 2000). Specifically, the bipolar electrode configuration with a 2 cm inter electrode distance was applied at the following locations: vastus lateralis; 66% along the line from the anterior spina iliaca superior to the lateral side of the patella, biceps femoris; 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles, 2013). EMG was sampled at a rate of 2000 Hz and anti-aliased with a 500 Hz low pass filter. A 10 Hz high pass filter was also applied. The Biopac MP100 system had an input impedance and common mode rejection ratio of 2MΩ and >110 dB, respectively.

EMG data processing

EMG signals were root mean square processed. Average root mean square was calculated for a moving window 100 ms time period across the entire waveform for each activity. Root mean square processing was used to analyse EMG based on previous recommendations for research investigating neuromuscular activation levels

(Hägg et al., 2004). Root mean square processing was conducted by the software used to operate the EMG system (AcqKnowledge® 3.8.1, Biopac Systems Inc, California, USA), in accordance with the manufacturer's guidelines (Acqknowledge® software guide, 2008).

Extraction of processed EMG data from normalisation tasks and dynamic back squat exercise sets

MVC and MIS normalisation methods. The three MVCs and MISs conducted during each session were analysed to determine which produced the greatest peak torque and peak force value, respectively. The mean EMG amplitude from the middle 3 s period of the 5 s peak torque MVC and peak force MIS from each test day was used to produce two separate isometric normalisation values (Albertus-Kajee et al., 2010). The use of synchronised channels of the EMG system displaying torque from the dynamometer (during MVCs) and channel spikes when metronome tones sounded (during the MIS) permitted the selection of the central 3 s period of each maximal isometric task for analysis.

60%, 70%, and 80% of 3RM normalisation tasks and dynamic back squat exercise sets. The mean root mean square processed EMG amplitude from each concentric and eccentric phase across back squat repetitions during the 60%, 70%, and 80% of 3RM normalisation tasks, and dynamic back squat sets was extracted. Concentric and eccentric back squat EMG data were identified based on synchronised knee joint angle data obtained from a two-dimensional electrogoniometer and integrated AcqKnowledge® software. The period from the greates to the smallest knee joint angle of the squat was identified as the eccentric phase of the back squat repetitions. The period from the smallest to the greatest knee joint angle of the squat was identified as the concentric phase of the back squat repetitions. The EMG from the 60%, 70%, and 80% of 3RM tasks was used to produce three separate normalisation task reference values for each muscle action phase. The EMG taken from each repetition during dynamic back squat sets was reported as a percentage of each normalisation task EMG value (e.g. (concentric EMG value from repetition one in the 65% of 3RM dynamic back squat exercise set ÷ MVC normalisation task EMG value) x 100). Subsequently, a mean normalised EMG value for each dynamic back squat set intensity and muscle action phase was calculated for each of the five normalisation methods. Therefore, five normalised EMG data sets per participant within each subsequent test day session were generated for each muscle action phase.

2.2.5 Statistical analysis

The distribution of data within the current study was assessed using Q-Q plots. Subsequently, normal distribution of data was confirmed. In an attempt to address the diverse use of reliability statistics within the EMG normalisation method literature, a range of measures were reported in the current study. Absolute reliability represents the level of within-individual variance when the same participant reports for repeated test sessions (Atkinson and Nevill, 1998). This measure was assessed via intra-participant coefficient of variation and limits of agreement. Intra-participant coefficient of variation was calculated for mean concentric and eccentric EMG from each different intensity dynamic back squat exercise set reported as a percentage of each normalisation method, as previously detailed (Albertus-Kajee et al., 2011). Intra-participant coefficent of variation standards were adopted from previous electromyography research and were defined as follows: <12.0%= “good”, 12.0-20%= “acceptable”, >20.0%= “unacceptable” (Albertus-Kajee et al., 2010). Intra-participant coefficient of variation was also calculated for peak MVC torque and maximal isometric squat force, in order to assess the output of each of these tasks. The practice of calculating intra-participant coefficients of variation for normalisation task kinetic or kinematic outputs has previously been used as an additional way of confirming normalisation task standardisation (Albertus-Kajee et al., 2011; Ball and Scurr, 2010). Limits of agreement for each normalisation method were calculated as previously detailed (Bland and Altman, 1986). Between-day differences in normalised dynamic back squat set EMG (produced during the calculation of limits of agreement) for each of the five normalisation methods were also reported as an additional absolute reliability measure (Gant et al., 2006).

Relative reliability is the extent to which participant order (based on ranking for a particular variable) varies when the same group of individuals are tested on repeat occasions (Atkinson and Nevill, 1998). Intraclass correlation coefficient was used to assess relative reliability. The classification of intraclass correlation coefficient results was adopted from recent normalisation method research also completing between-day measures (Albertus-Kajee et al., 2011; Albertus-Kajee et al., 2010). Where negative intraclass correlation coefficient values were displayed this was taken to denote greater within-participant than between-participant variance (Larsson et al., 1999). Intraclass correlation coefficient values and 95% confidence intervals were calculated with statistical spreadsheets downloaded from www.sportsci.org (Hopkins, 2010).

Minitab 15 statistical software (Minitab Ltd., Coventry, UK) was used to conduct a normalisation method (MVC *vs.* MIS *vs.* 60% of 3RM *vs.* 70% of 3RM *vs.* 80% of 3RM) x dynamic back squat set load (65% of 3RM *vs.* 75% of 3RM *vs.* 85% of 3RM *vs.* 95% of 3RM) repeated measures analysis of variance for EMG from each muscle action phase on all three test days in order to assess sensitivity. The ability of each normalisation method to detect statistical differences between load increments on consecutive test days was used as a way of quantifying sensitivity levels (Albertus-Kajee et al., 2010). In addition, a repeated measures analysis of variance (65% of 3RM *vs.* 75% of 3RM *vs.* 85% of 3RM *vs.* 95% of 3RM) was conducted on the unnormalised EMG taken from the dynamic back squat exercise sets on a single test day session (test day three). This analysis allowed for the sensitivity of the unnormalised EMG data to be assessed. A significance level of $p < 0.05$ was selected to determine statistical differences. Tukey *post-hoc* analysis was used to determine where differences occurred with load increment during dynamic back squat sets for each normalisation method and the corresponding unnormalised EMG values.

Inter-participant variability is the extent of the differences displayed between participants within a sample for a given measure, providing an indication of the spread of values of the measure in relation to the sample mean (Knutson et al., 1994). Inter-participant coefficient of variation was used to assess inter-participant variability and determine if a “common” (<12.0%) level of neuromuscular recruitment was displayed across dynamic back squat sets for a homogeneous strength-trained participant sample (Hug et al., 2004). Inter-participant coefficient of variation for each different intensity dynamic back squat exercise set was calculated for every normalisation task on each test day, for both muscle action phases as previously described (Bolgla and Uhl, 2007). Inter-participant coefficient of variation was also calculated for unnormalised EMG for test day three to allow comparison between inter-participant variability with and without the use of normalisation.

2.3 Results

2.3.1 Absolute reliability of peak kinetic measures from the MVC and MIS normalisation methods

In order to address potential motivational issues and standardise maximal isometric normalisation tasks, the absolute reliability of the MVC (peak torque, N.m) and MIS (peak force, N) kinetic outputs were calculated. The MVC and maximal isometric squat normalisation tasks produced coefficient of variation values of 8.0 ± 3.9% and 4.8 ± 2.4% (mean ± SD), respectively.

2.3.2 Absolute reliability of the normalisation methods

Table 2.1 details unnormalised EMG data from subsequent test day three, whereas Tables 2.2 and 2.3 display normalised EMG averaged across test day sessions. It has previously been stated that the use of coefficient of variation depends greatly on the magnitude of the normalisation tasks; hence exercise activities using normalisation tasks with smaller amplitudes inherently display smaller coefficient of variation values (Burden, 2010; Burden et al., 2003). Therefore, only maximal isometric or submaximal normalisation tasks were compared to each other for intra-participant coefficient of variation results. The MIS normalisation method produced smaller (4.5-8.2% smaller) intra-participant coefficient of variation values than the MVC method for the vastus lateralis in both concentric and eccentric muscle actions (Table 2.4). The MIS normalisation method also produced smaller intra-participant coefficient of variation values compared to the MVC method for the biceps femoris during concentric and eccentric actions. However, intra-participant coefficient of variation values were much more similar for the biceps femoris than the vastus lateralis (MIS 1.6-1.9% smaller than the MVC normalisation method, Table 2.5). The 80% of 3RM-normalisation method displayed smaller intra-participant coefficient of variation values than both the 60% and 70% of 3RM methods for the vastus lateralis during concentric and eccentric muscle actions (2.1-7.2% smaller, Table 2.4). The biceps femoris intra-participant coefficient of variation values were similar to the vastus lateralis, with the 80% of 3RM normalisation method displaying smaller coefficient of variation values than both 60% of 3RM and 70% of 3RM methods (0.8-6.3% smaller, Table 2.5), for both muscle actions.

The limits of agreement intra-participant reliability measure is based on the difference scores between-test days and the SD of the difference scores (Hopkins, 2000; Bland and Altman, 1986). The coefficient of variation is influenced by the ratio of the mean and SD of the normalisation output (Burden, 2010). However, the limits of agreement are not affected by the same problem. Therefore, limits of agreement results for all normalisation methods were compared. The 80% of 3RM task demonstrated narrower 95% limits of agreement range values for the vastus lateralis during both muscle actions compared to the other normalisation methods (Table 2.4).

Table 2.1 Unnormalised root mean square processed vastus lateralis and biceps femoris EMG amplitude (mV) during the normalisation tasks and investigated exercise activities from subsequent test day session three. Unnormalised values are presented for both maximal isometric normalisation tasks, whereas concentric and eccentric values are presented for dynamic normalisation tasks and the investigated dynamic back squat exercise. Additionally, inter-participant variability for the unnormalised EMG is reported as inter-participant coefficient of variation.

		Vastus lateralis						Biceps femoris					
		Mean	±	SD				Mean	±	SD			
Isometric normalisation tasks	MVC	0.95	±	0.53				0.06	±	0.02			
	MIS	1.02	±	0.63				0.14	±	0.10			
	Muscle Action	Concentric			Eccentric			Concentric			Eccentric		
		Mean	±	SD	Mean	±	SD	Mean	±	SD	Mean	±	SD
Dynamic normalisation tasks	60% of 3RM	0.70	±	0.32	0.39	±	0.16	0.12	±	0.07	0.06	±	0.01
	70% of 3RM	0.81	±	0.40	0.45	±	0.18	0.16	±	0.11	0.07	±	0.02
	80% of 3RM	0.90	±	0.44	0.52	±	0.21	0.19	±	0.12	0.08	±	0.02
Investigated exercise activity: dynamic back squat exercise sets	65% of 3RM	0.69	±	0.32	0.39	±	0.16	0.15	±	0.10	0.06	±	0.02
	75% of 3RM	0.75	±	0.33	0.46	±	0.18 ^{a}	0.16	±	0.10	0.07	±	0.02
	85% of 3RM	0.86	±	0.37 ^{A}	0.55	±	0.21 $^{A\ B}$	0.20	±	0.11 $^{A\ b}$	0.08	±	0.02 ^{a}
	95% of 3RM	1.00	±	0.42 $^{A\ B\ c}$	0.64	±	0.26 $^{A\ B\ C}$	0.26	±	0.14 $^{A\ B\ C}$	0.10	±	0.04 $^{A\ B\ c}$
Inter-participant coefficient of variation across back squat exercise sets		43.8	±	1.8	61.6	±	7.2	39.5	±	1.4	32.8	±	6.4

^{A,a} denotes significant difference from EMG at 65% of 3RM load. ^{B,b} denotes significant difference from EMG at 75% of 3RM load. ^{C,c} denotes significant difference from EMG at 85% of 3RM load. Lower case versions of each letter denote significant difference at $p < 0.05$ level, upper case letters denote significant difference at $p < 0.01$ level.

Table 2.2 Concentric and eccentric vastus lateralis EMG activity at each different intensity dynamic back squat exercise set reported as a percentage of each normalisation task.

		Normalisation method														
Muscle action phase	Dynamic back squat exercise set intensity	MVC			MIS			60% of 3RM			70% of 3RM			80% of 3RM		
		Mean	±	SD[#]	Mean	±	SD	Mean	±	SD	Mean	±	SD	Mean	±	SD
Concentric	65% of 3RM	74.6	±	24.5	77.0	±	22.3	98.8	±	8.6	88.0	±	5.7	78.4	±	7.8
	75% of 3RM	81.9	±	26.2	84.8	±	23.4	108.7	±	6.7	96.8	±	2.4	86.2	±	6.2
	85% of 3RM	94.9	±	33.1	97.0	±	27.3	125.8	±	17.0	111.6	±	9.2	99.2	±	6.9
	95% of 3RM	109.1	±	37.2	111.3	±	30.9	144.4	±	17.9	128.3	±	11.8	114.2	±	11.7
	Mean across sets	90.1	±	15.2	92.5	±	15.0	119.5	±	20.0	106.2	±	17.7	94.5	±	15.7
Eccentric	65% of 3RM	44.7	±	13.9	47.3	±	14.7	101.0	±	14.2	87.2	±	9.0	76.7	±	5.7
	75% of 3RM	51.9	±	16.9	54.7	±	17.4	117.2	±	16.8	100.9	±	9.1	88.7	±	4.6
	85% of 3RM	61.9	±	21.5	64.8	±	21.8	138.2	±	19.9	119.1	±	10.9	104.7	±	6.7
	95% of 3RM	71.4	±	25.2	74.1	±	23.5	159.7	±	23.9	137.8	±	14.7	120.9	±	10.0
	Mean across sets	57.5	±	11.6	60.2	±	11.7	129.0	±	25.5	111.3	±	22.0	97.7	±	19.3

Table 2.3 Concentric and eccentric biceps femoris EMG activity during dynamic back squat exercise sets reported as a percentage of each normalisation task.

		Normalisation method														
Muscle action phase	Dynamic back squat exercise set intensity	MVC			MIS			60% of 3RM			70% of 3RM			80% of 3RM		
		Mean	±	SD	Mean	±	SD	Mean	±	SD	Mean	±	SD	Mean	±	SD
Concentric	65% of 3RM	180.5	±	105.2	110.2	±	57.2	112.7	±	17.0	92.3	±	10.4	76.3	±	7.6
	75% of 3RM	202.7	±	100.7	128.6	±	67.7	128.7	±	14.3	105.4	±	8.7	87.0	±	6.8
	85% of 3RM	243.5	±	110.7	154.2	±	72.7	155.1	±	21.4	127.1	±	13.5	104.0	±	7.0
	95% of 3RM	332.9	±	170.1	208.4	±	88.0	182.5	±	25.2	168.9	±	22.4	137.5	±	13.5
	Mean across sets	239.9	±	67.3	150.3	±	42.7	144.7	±	30.7	123.4	±	33.5	101.2	±	26.7
Eccentric	65% of 3RM	103.2	±	34.7	51.3	±	26.6	104.2	±	12.3	90.2	±	8.2	76.2	±	7.0
	75% of 3RM	119.0	±	36.1	58.9	±	29.2	121.2	±	17.0	104.8	±	12.1	88.5	±	8.3
	85% of 3RM	140.9	±	40.7	70.7	±	35.9	145.5	±	21.4	125.4	±	16.0	105.5	±	10.4
	95% of 3RM	179.9	±	61.0	88.1	±	43.6	187.7	±	54.1	161.5	±	42.5	134.9	±	29.5
	Mean across sets	135.8	±	33.2	67.3	±	16.0	139.7	±	36.2	120.5	±	30.9	101.3	±	25.4

Table 2.4 Summary of concentric and eccentric phase vastus lateralis EMG absolute reliability measures for the five normalisation methods across different intensity dynamic back squat exercise sets.

		Difference between test days			95% Upper limits of agreement			95% Lower limits of agreement			Intra-participant coefficient of variation			Coefficient of variation descriptor
Muscle action phase	Normalisation method	Mean	±	SD	Mean	±	SD	Mean	±	SD	Mean	±	SD	
Concentric	MVC	15.1	±	3.6	83.6	±	17.8	-53.5	±	11.2	24.3	±	0.5	Unacceptable
	MIS	1.3	±	1.8	54.8	±	3.7	-52.1	±	4.7	16.1	±	2.2	Acceptable
	60% of 3RM	0.0	±	2.2	39.8	±	8.3	-39.7	±	6.4	10.2	±	0.6	Good
	70% of 3RM	0.1	±	1.9	30.8	±	2.1	-30.7	±	2.2	9.7	±	1.6	Good
	80% of 3RM	0.4	±	1.7	22.7	±	3.8	-22.0	±	2.1	7.6	±	1.1	Good
Eccentric	MVC	9.2	±	2.8	51.3	±	13.0	-33.0	±	7.8	21.7	±	0.5	Unacceptable
	MIS	0.5	±	1.3	37.2	±	8.4	-36.2	±	6.5	17.2	±	1.6	Acceptable
	60% of 3RM	3.0	±	3.0	67.1	±	15.5	-61.1	±	10.8	14.2	±	0.8	Acceptable
	70% of 3RM	1.1	±	2.4	41.3	±	12.7	-39.1	±	9.9	10.3	±	0.4	Good
	80% of 3RM	0.7	±	2.1	23.3	±	8.2	-22.0	±	6.0	7.0	±	0.4	Good

Table 2.5 Summary of concentric and eccentric phase biceps femoris EMG absolute reliability measures for the five normalisation methods across different intensity dynamic back squat exercise sets.

		Difference between test days			95% Upper limits of agreement			95% Lower limits of agreement			Intra-participant coefficient of variaition			Coefficient of variation descriptor
Muscle action phase	Normalisation method	Mean	±	SD	Mean	±	SD	Mean	±	SD	Mean	±	SD	
Concentric	MVC	40.4	±	10.4	304.0	±	69.7	-223.2	±	49.1	28.5	±	1.1	Unacceptable
	MIS	8.5	±	4.2	129.7	±	39.7	-112.7	±	32.3	26.6	±	1.0	Unacceptable
	60% of 3RM	-30.1	±	19.9	30.2	±	7.2	-90.4	±	33.4	18.9	±	4.1	Acceptable
	70% of 3RM	-17.3	±	14.9	35.8	±	13.1	-70.5	±	42.2	16.3	±	5.9	Acceptable
	80% of 3RM	-6.6	±	10.4	28.5	±	6.5	-41.7	±	24.1	12.6	±	3.5	Acceptable
Eccentric	MVC	20.1	±	3.9	106.9	±	24.6	-66.8	±	21.2	22.5	±	0.8	Unacceptable
	MIS	7.1	±	1.3	45.5	±	14.4	-31.3	±	13.0	20.9	±	2.9	Unacceptable
	60% of 3RM	-0.5	±	2.8	63.5	±	27.8	-64.5	±	30.1	12.5	±	1.6	Acceptable
	70% of 3RM	-3.1	±	3.3	58.0	±	24.4	-64.1	±	29.1	12.5	±	1.0	Acceptable
	80% of 3RM	0.1	±	2.4	40.2	±	9.3	-40.0	±	11.7	11.7	±	1.6	Good

Table 2.6 Summary of concentric and eccentric phase vastus lateralis and bicep femoris EMG relative reliability (intraclass correlation coefficient) and inter-participant variability (inter-participant coefficient of variaition) measures for the five normalisation methods across dynamic back squat exercise sets.

		Vastus lateralis						Biceps femoris					
		Intraclass correlation coefficent			Inter-participant coefficient of variation			Intraclass correlation coefficent			Inter-participant coefficient of variation		
Muscle action phase	Normalisation method	Mean	LCI[$]	UCI[$$]	Mean	±	SD	Mean	LCI	UCI	Mean	±	SD
Concentric	MVC	0.57	0.19	0.85	39.5	±	1.2	0.70	0.37	0.91	56.3	±	4.2
	MIS	0.62	0.26	0.88	32.8	±	1.2	0.73	0.42	0.92	53.2	±	3.8
	60% of 3RM	0.13	-0.20	0.59	14.0	±	2.4	0.30	-0.08	0.71	17.6	±	1.8
	70% of 3RM	-0.02	-0.29	0.45	11.1	±	0.9	0.27	-0.10	0.69	15.7	±	2.8
	80% of 3RM	0.34	-0.05	0.74	10.8	±	1.5	0.13	-0.20	0.59	13.0	±	2.2
Eccentric	MVC	0.56	0.18	0.85	38.7	±	1.9	0.60	0.23	0.87	36.6	±	2.6
	MIS	0.70	0.37	0.91	36.0	±	0.9	0.87	0.68	0.96	52.9	±	0.4
	60% of 3RM	0.05	-0.25	0.52	20.6	±	0.4	0.42	0.02	0.78	21.0	±	7.5
	70% of 3RM	0.14	-0.20	0.60	14.3	±	1.2	0.23	-0.13	0.67	19.3	±	6.9
	80% of 3RM	0.27	-0.10	0.69	9.5	±	1.4	0.30	-0.08	0.72	17.1	±	4.7

[$] lower confidence interval, [$$] upper confidence interval.

Concentric muscle actions for the biceps femoris displayed the 80% of 3RM normalisation method to have the narrower 95% limits of agreement range values. The 80% of 3RM and MIS normalisation methods displayed similar 95% limits of agreement values for the biceps femoris during the eccentric muscle action (Table 2.5).

2.3.3 Relative reliability of the normalisation methods

The normalisation method displaying the highest intraclass correlation coefficient value for the vastus lateralis during both muscle actions was the MIS normalisation method (Table 2.6). The intraclass correlation coefficient values obtained for the vastus lateralis during both muscle action phases for the MIS normalisation method were classified as “fair” (0.60-0.79), based on standards defined within the existing normalisation method research (Albertus-Kajee et al., 2010; Sleivert and Wenger, 1994). All other normalisation methods displayed “poor” (<0.60) intraclass correlation coefficient values for the vastus lateralis. The MIS normalisation method also displayed the highest intraclass correlation coefficient values for the biceps femoris during both concentric (“fair”) and eccentric (“good” (0.80-1.00)) muscle actions (Table 2.6). The MVC normalisation method achieved “fair” intraclass correlation coefficient classification for the biceps femoris for both muscle actions. All other normalisation methods displayed “poor” intraclass correlation coefficient values for the biceps femoris during both muscle action phases.

2.3.4 Sensitivity of the normalisation methods

Normalised EMG data for the dynamic back squat exercise sets were reported for each trial day (Figure 2.3 and 2.4) to avoid reduction of the SD by averaging across trial days (Albertus-Kajee, 2008). Load effects were demonstrated for MVC, MIS, 60% of 3RM, 70% of 3RM, and 80% of 3RM normalisation methods on all three test days (Table 2.7). During both muscle action phases for the vastus lateralis the MIS, 60% of 3RM, 70% of 3RM, and 80% of 3RM normalisation methods were the most sensitive to load increments. These methods were the most sensitive as they more consistently differentiated between increases in neuromuscular activation with a greater number of load increments than the MVC normalisation method (Figure 2.3 A-C and 2.4 A-C). During the eccentric phase for the vastus lateralis these methods were able to differentiate between all load increments on each test day. However, for the vastus lateralis during the concentric phase on two of the three test days neuromuscular activation levels could not be differentiated between the 65% of 3RM and 75% of 3RM loads for any normalisation method. During the concentric phase for the biceps femoris the 60% of 3RM, 70% of 3RM, and 80% of 3RM normalisation methods were more sensitive than the isometric normalisation methods (Figure 2.3 D-F and 2.4 D-F). The MVC, 60% of 3RM, and 70% of 3RM normalisation methods most consistently differentiated between neuromuscular activation levels for a greater number of load increments during the eccentric phase for the biceps femoris. The most consistently sensitive normalisation methods for the biceps femoris failed to differentiate between neuromuscular activation levels for the 65% of 3RM to 75% of 3RM load increment during both muscle action phases. In addition, the most consistently sensitive normalisation methods failed to differentiate between biceps femoris neuromuscular activation with load increments between 75% of 3RM and 85% of 3RM on two of the three test days (Figure 2.3 D-F and 2.4 D-F).

The comparison between the most consistently sensitive normalisation methods and unnormalised EMG values on test day three revealed similar levels of sensitivity. Unnormalised EMG was able to differentiate between the same number of load increments as the most sensitive normalisation methods for both muscle action phases for the biceps femoris and for the eccentric phase for the vastus lateralis (Table 2.1, Table 2.7, Figure 2.3 F, and Figure 2.4 C and F). However, unnormalised EMG was not able to differentiate between the same number of load increments as the most sensitive normalisation methods for the vastus lateralis during concentric muscle actions (Table 2.1 and Figure 2.3 C).

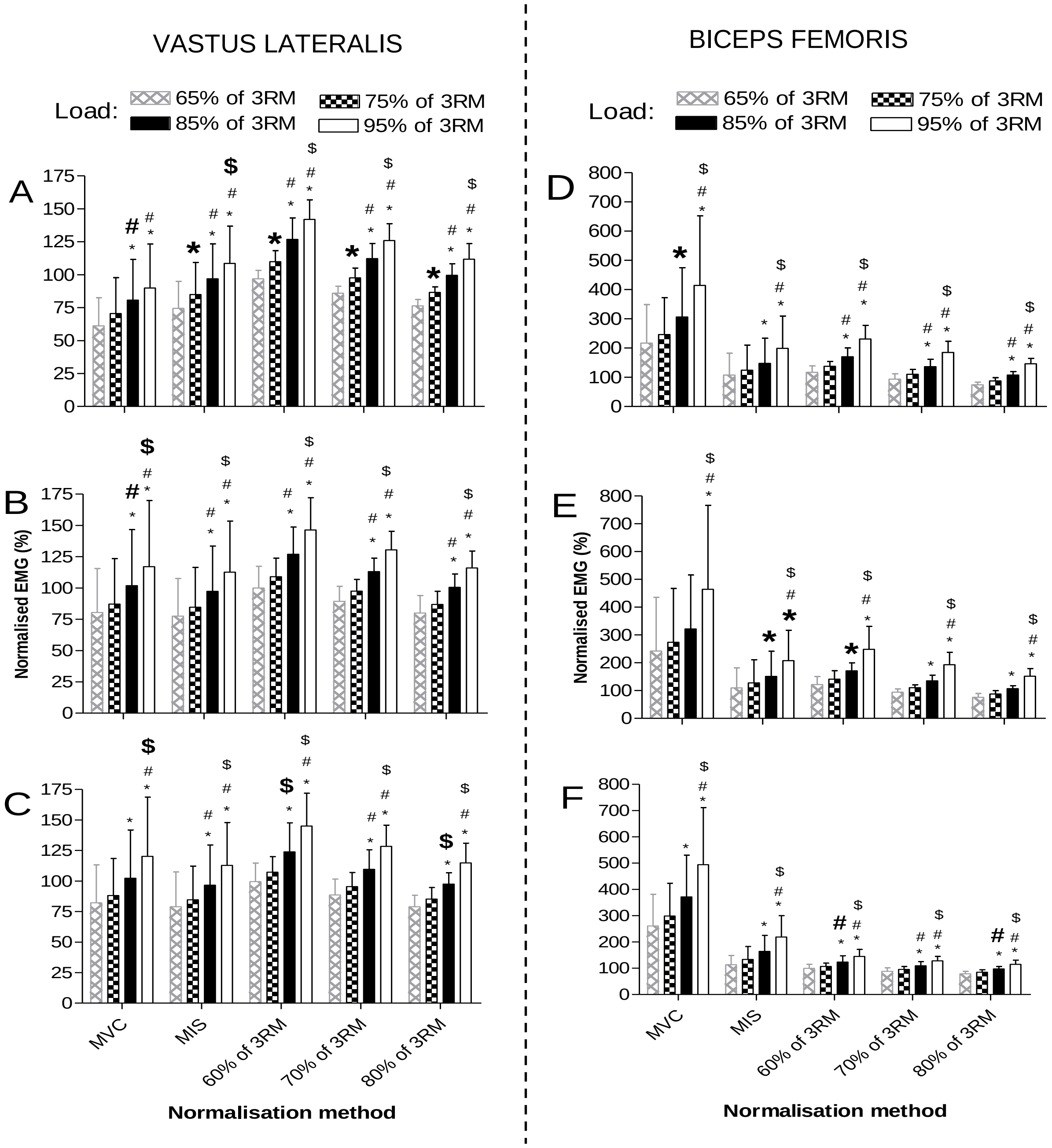


Figure 2.3 Concentric EMG for each normalisation method across dynamic back squat sets for the vastus lateralis (A-C) and biceps femoris (D-F). The bar charts display where significant differences occurred between different intensity back squat sets for each normalisation method for test session day one (A, D), day two (B, E) and day three (C, F). * denotes significant difference from EMG at 65% of 3RM load. # denotes significant difference from EMG at 75% of 3RM load. $ denotes significant difference from EMG at 85% of 3RM load. Symbols (*, #, $) in bold and enlarged denote significant difference at $p < 0.05$ level, symbols not in bold denote significant difference at $p < 0.01$ level.

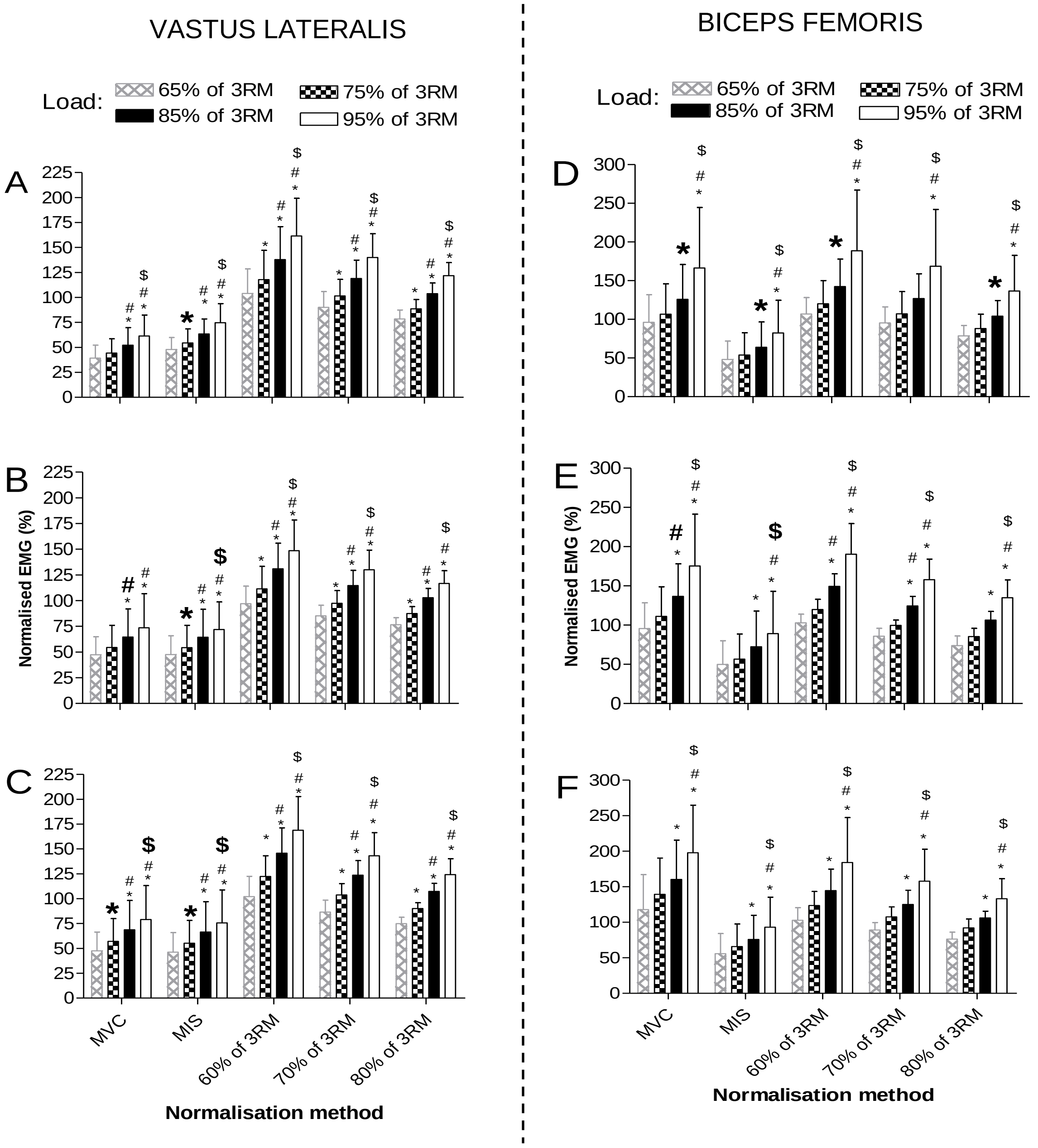


Figure 2.4 Eccentric EMG for each normalisation method across dynamic back squat sets for the vastus lateralis (A-C) and biceps femoris (D-F). The bar charts display where significant differences occurred between different intensity back squat sets for each normalisation method for test session day one (A, D), day two (B, E) and day three (C, F). * denotes significant difference from EMG at 65% of 3RM. # denotes significant difference from EMG at 75% of 3RM. $ denotes significant difference from EMG at 85% of 3RM. Symbols (*, #, $) in bold and enlarged denote significant difference at $p < 0.05$ level, symbols not in bold denote significant difference at $p < 0.01$ level.

Table 2.7 Repeated measures analysis of variance load effect p- and f-value results for each normalisation method and unnormalised EMG from subsequent test day three.

	Muscle action phase	Concentric				Eccentric			
	Muscle	Vastus lateralis		Biceps femoris		Vastus lateralis		Biceps femoris	
Normalisation method	Day	p	f	p	f	p	f	p	f
MVC	1	<0.001	24.13	<0.001	21.88	<0.001	43.81	<0.001	16.80
	2	<0.001	21.04	<0.001	17.75	<0.001	23.72	<0.001	30.48
	3	<0.001	19.76	<0.001	28.88	<0.001	33.42	<0.001	25.18
MIS	1	<0.001	36.08	<0.001	30.54	<0.001	69.26	<0.001	18.50
	2	<0.001	37.60	<0.001	23.21	<0.001	42.30	<0.001	16.84
	3	<0.001	40.64	<0.001	32.56	<0.001	31.42	<0.001	20.82
60% of 3RM	1	<0.001	40.43	<0.001	58.87	<0.001	79.06	<0.001	16.29
	2	<0.001	33.38	<0.001	22.45	<0.001	69.52	<0.001	45.63
	3	<0.001	30.08	<0.001	30.08	<0.001	65.70	<0.001	18.94
70% of 3RM	1	<0.001	42.05	<0.001	60.85	<0.001	94.49	<0.001	15.48
	2	<0.001	40.99	<0.001	33.46	<0.001	82.60	<0.001	54.57
	3	<0.001	36.91	<0.001	36.91	<0.001	68.09	<0.001	20.27
80% of 3RM	1	<0.001	41.23	<0.001	72.67	<0.001	117.15	<0.001	20.66
	2	<0.001	44.85	<0.001	38.56	<0.001	95.33	<0.001	60.80
	3	<0.001	33.98	<0.001	33.98	<0.001	71.57	<0.001	23.16
Unnormalised EMG	3	<0.001	16.69	<0.001	37.46	<0.001	41.96	<0.001	15.21

2.3.5 Inter-participant variability of the normalisation methods

Similar to intra-participant coefficient of variation, inter-participant coefficient of variation also depends on the magnitude of the normalisation task amplitude (Burden, 2010). Therefore, only maximal isometric or submaximal normalisation tasks were compared to each other for inter-participant coefficient of variation results. The MIS normalisation method displayed smaller inter-participant coefficient of variation values for both muscle actions for the vastus lateralis compared to MVC normalisation method (2.7-6.7% smaller, Table 2.6). Coefficient of variation values for the biceps femoris were smaller for the MIS method (3.1% smaller) compared to the MVC task during the concentric phase. However, the biceps femoris coefficient of variation was smaller for the MVC method (16.3% smaller) compared to the MIS task during the eccentric phase. The 80% of 3RM normalisation method displayed smaller coefficient of variation values across muscle actions for both the vastus lateralis and biceps femoris (0.3-11.1% smaller) compared to the 60% of 3RM and 70% of 3RM methods (Table 2.6). In comparison to the inter-participant coefficient of variation calculated for the unnormalised EMG from the dynamic back squat exercise sets (on test day three) the use of the dynamic normalisation methods (60% of 3RM, 70% of 3RM, and 80% of 3RM) reduced the inter-participant coefficient of variation during both muscle actions for the vastus lateralis and biceps femoris (Tables 2.1 and 2.6). The use of the isometric normalisation methods (MVC and MIS) reduced the inter-participant coefficient of variation compared to the unnormalised EMG coefficient of variation during both muscle actions phases for the vastus lateralis but not the biceps femoris (Tables 2.1 and 2.6). The 70% of 3RM (concentric phase) and 80% of 3RM (concentric and eccentric phases) tasks were the only normalisation methods to display inter-participant coefficient of variations below 12.0%, which was the threshold set for defining “common” neuromuscular recruitment levels between participants (Hug et al., 2004).

2.4 Discussion

2.4.1 Absolute reliability of the normalisation methods

The first aim of the present study was to evaluate the reliability of different EMG normalisation methods for the free weight back squat. The results of the study provide novel data to the existing EMG normalisation methodology literature. In terms of absolute reliability, it was demonstrated that the MIS method provided a smaller coefficient of variation and a narrower limits of agreement range than the MVC normalisation method. The mean intra-participant coefficient of variation values from the MVC normalisation method for both concentric and eccentric phases of the back squat were extremely similar to those recently reported in the same muscles for MVC normalisation for running (Albertus-Kajee et al., 2011). However, intra-participant coefficient of variation values tended to be higher than those from MVC normalisation for the vastus lateralis and biceps femoris during cycling (Rouffet and Hautier, 2008) and MVCs of the triceps surae (Ball and Scurr, 2010). Furthermore, the coefficient of variation values reported here for MVC and MIS normalisation methods are considerably smaller than those documented for MVC normalisation of the medial gastrocnemius during a balance board exercise (Knutson et al., 1994). The MIS normalisation method produced similar coefficient of variation values for the two investigated muscles as those reported for MVC methods in previous studies (Ball and Scurr, 2010; Rouffet and Hautier, 2008).

The 80% of 3RM method demonstrated smaller intra-participant coefficient of variation compared to the other submaximal dynamic normalisation methods (60% of 3RM and 70% of 3RM) and smaller 95% limits of agreement ranges compared to all other methods (including MVC and MIS). The 80% of 3RM intra-participant coefficient of variation values reported in the current study were smaller than those recently reported for a submaximal dynamic normalisation method for running (Albertus-Kajee et al., 2011). In addition, the 80% of 3RM normalisation method displayed smaller intra-participant coefficient of variation values than those reported for submaximal isometric normalisation tasks for the vastus lateralis (Mathur et al., 2005) and triceps surae (Ball and Scurr, 2010).

The coefficient of variation has been used extensively in the research literature but comparing maximal and submaximal normalisation tasks is problematic, as the amplitude of submaximal tasks can reduce the coefficient of variation (Burden, 2010; Burden et al., 2003). Smaller coefficients of variation produced from submaximal compared to maximal normalisation tasks may not actually represent better absolute reliability. Therefore, within the current study only maximal or submaximal normalisation tasks were compared for intra-participant coefficient of variation. The coefficient of variation has other limitations that have previously been detailed, such that normalised EMG from a task may not always be within the coefficient of variation established and may underestimate absolute reliability in future participants (Atkinson and Nevill, 1998). However, the measure represents mainly biological variation, is easily applied to new participants, and is not influenced by participant sample size (Ball and Scurr, 2010; Hopkins, 2000).

Limits of agreement have not previously been reported in the normalisation literature. Therefore, comparisons could not be made to the current study. Limits of agreement allow the comparison of maximal and submaximal normalisation methods as they are not influenced by the same issues that apply with the coefficient of variation. Limits of agreement are calculated on differences between repeated tests, not on the mean and SD of such tests, as with the coefficient of variation (Burden, 2010; Hopkins, 2000). However, the limits of agreement are affected by sample size unlike the coefficient of variation (Atkinson and Nevill, 1998). Therefore, larger participant samples strengthen the use of the limits of agreement. Nevertheless, it is not always possible to recruit large participant samples when investigating highly specific populations. Other concerns regarding the use of 95% limits of agreement levels are that this measure may be too stringent and meaningful improvements or adaptations may be overlooked (Hopkins, 2000).

The greater absolute reliability of the 80% of 3RM normalisation method, as demonstrated from the limits of agreement results, compared to the maximal isometric methods may be explained by the highly similar nature of this normalisation task to the investigated activity (dynamic back squat exercise sets). Given the muscle actions, velocity, and range of movement of the 80% of 3RM normalisation method was the same as that of the dynamic back squat exercise sets, this seems a logical explanation. However, the contribution of elastic energy storage and utilisation during the dynamic submaximal dynamic back squat normalisation tasks cannot be directly accounted for in the current study. The apparent similarity between the 80% of 3RM normalisation method and dynamic back squat exercise sets does not however explain why during the eccentric phase of the back squat the MVC (vastus lateralis and biceps femoris) and MIS (vastus lateralis) methods demonstrated better limits of agreement values than the 60% of 3RM and 70% of 3RM methods. This difference remains to be elucidated, but may be a related to the differential muscle recruitment strategies believed to be involved in the performance of eccentric and concentric muscle actions (Enoka, 1996). Regardless of this issue, normalising concentric vastus lateralis and biceps femoris EMG from the dynamic back squat exercise sets to a very similar reference task may better account for biological variance in neuromuscular recruitment strategies for this specific muscle action, compared to unrelated isometric tasks. The limits of agreement results presented suggest that researchers aiming to assess individual vastus lateralis and biceps femoris EMG responses or adaptations during the back squat exercise should normalise to the 80% of 3RM normalisation task, as opposed to conventional or alternate maximal isometric tasks.

2.4.2 Relative reliability of the normalisation methods

The other aspect of the first aim of the current study concerned relative reliability of the investigated normalisation methods. If the research question proposed for a given study involves comparisons of neuromuscular activation between individuals, the normalisation method selected should demonstrate good relative reliability. The relative reliability results of the current study add new information to the existing research literature, as it was demonstrated the MIS normalisation method had the greatest relative reliability for vastus lateralis and biceps femoris EMG during concentric and eccentric muscle actions across dynamic back squat exercise sets. However, this task displayed only “fair” intraclass correlation coefficient classifications, except for eccentric biceps femoris EMG where relative reliability was “good”. All dynamic normalisation methods displayed “poor” relative reliability for both vastus lateralis and biceps femoris EMG across dynamic back squat set loads.

The intraclass correlation coefficient results of the current study are in contrast to recently published findings. Cycling and running studies have demonstrated maximal dynamic (Albertus-Kajee et al., 2011) and submaximal dynamic normalisation methods (Albertus-Kajee et al., 2010) to have better relative reliability for the vastus lateralis and biceps femoris than equivalent MVC tasks. MVC and dynamic normalisation method intraclass correlation coefficients have been demonstrated to be similar for hip musculature exercise tasks (Bolgla and Uhl, 2007). The intraclass correlation coefficient is useful for calculating correlations for investigations involving multiple measures (Hopkins, 2000; Atkinson and Nevill, 1998). However, interpretation of the intraclass correlation coefficient should not be made without supporting reliability statistics (Atkinson and Nevill, 1998). The current study demonstrated the MIS method to provide better relative reliability for the vastus lateralis and biceps femoris compared to other back squat normalisation methods. These results suggest that researchers aiming to compare vastus lateralis and biceps femoris neuromuscular activation between experienced strength-trained individuals should use the MIS task when investigating concentric and eccentric muscle actions during the dynamic free weight back squat.

2.4.3 Sensitivity of the normalisation methods

The second aim of the study was to examine the ability of each method to statistically differentiate between neuromuscular activation levels at different dynamic back squat exercise intensities. The sensitivity findings from the current study provide novel information to the research literature as the 60% of 3RM and 70% of 3RM methods most consistently differentiated between load increments for the two muscles, across the concentric and eccentric phases. The current study produced similar findings to recent cycling EMG normalisation research identifying dynamic normalisation methods to better separate vastus lateralis and biceps femoris EMG with power output increments than an MVC method (Albertus-Kajee et al., 2010). However, research from the same group demonstrated MVC and dynamic normalisation methods to be equally sensitive to increments in running speed for vastus lateralis and biceps femoris EMG (Albertus-Kajee et al., 2011).

As raw EMG during the dynamic back squat exercise sets produced five different data sets when referenced to each normalisation task, it can be confirmed the amplitude of the 60% of 3RM and 70% of 3RM methods were responsible for the current sensitivity findings. These methods displayed greater sensitivity for eccentric and concentric vastus lateralis and biceps femoris EMG compared to the other methods. The fact that the 60% of 3RM and 70% of 3RM tasks produce smaller reference values than the other normalisation tasks likely explains this finding. However, this does not explain why the other higher amplitude normalisation tasks were found to be equally sensitive for single muscle actions in one but not both of the investigated muscles.

The other finding from the current study with regard to sensitivity was unnormalised EMG was equally as sensitive as the 60% of 3RM and 70% of 3RM normalisation methods, except for the vastus lateralis during the concentric phase. Previous studies investigating elbow flexion-extension exercise have reported similar findings. During this upper-body exercise it was demonstrated that unnormalised EMG

(Burden and Bartlett, 1999; Allison et al., 1993), MVC (Allison et al., 1993) and dynamic normalisation reference values taken from within the investigated task (Burden and Bartlett, 1999; Allison et al., 1993) were sensitive to load increment. Furthermore, unnormalised EMG and MVC methods have been reported to demonstrate greater sensitivity compared to dynamic within task normalisation values. However, this was noted to be due to the use of different normalisation values at each different intensity load, for each dynamic normalisation method (Burden and Bartlett, 1999). This issue was not encountered in the present study as separate dynamic normalisation methods were employed. These sensitivity results suggest researchers interested in investigating differences in vastus lateralis and biceps femoris neuromuscular activity with load increment during the back squat should use the 60% of 3RM or 70% of 3RM normalisation methods.

2.4.4 Inter-participant variability of the normalisation methods and unnormalised EMG

The third aim of the current study was to assess the extent of neuromuscular activation heterogeneity in a group of strength-trained individuals experienced in performing the back squat exercise. Inter-participant variability has previously been used to determine normal EMG profiles during tasks such as walking (Winter and Yack, 1987) and the extent of homogeneity in neuromuscular recruitment patterns in elite cyclists (Hug et al., 2004). The findings of the current study add to the existing normalisation method literature as it was demonstrated “common” neuromuscular recruitment strategies were only displayed for the 70% of 3RM and 80% of 3RM tasks and not by either maximal isometric method or unnormalised EMG. It would be expected that a group of individuals with similar strength levels and back squat training experience would display similar neuromuscular activation levels, regardless of the normalisation method employed. However, this was not the case. Previous research has reported a highly homogeneous group of professional endurance-trained cyclists not to display “common” muscle activation patterns, although normalisation values were derived from within the investigated task in this study (Hug et al., 2004). The inter-participant variability of the maximal isometric methods was smaller than the majority of previous studies detailing variability with MVC normalisation (Bolgla and Uhl, 2007; Hunter et al., 2002; Knutson et al., 1994). However, the inter-participant variability for maximal isometric methods was higher than the results of other studies (Rouffet and Hautier, 2008).

The majority of research investigating inter-participant variability using dynamic normalisation methods has used normalisation reference values taken from within the investigated task (Bolgla and Uhl, 2007; Burden and Bartlett, 1999; Knutson et al., 1994; Allison et al., 1993; Yang and Winter, 1984). The current study used normalisation reference values taken from separate dynamic normalisation tasks, as it had previously been noted that the use of within-task normalisation values can negatively affect sensitivity (Burden and Bartlett, 1999). The findings presented from the current study demonstrate smaller inter-participant coefficient of variation values for submaximal normalisation methods compared to those previously detailed for normalisation values derived from the dynamic task investigated (Bolgla and Uhl, 2007; Knutson et al., 1994; Yang and Winter, 1984). Although, comparisons of inter-participant coefficient of variation values between different intensity dynamic normalisation reference values from separate studies may be problematic due to the limitations of the coefficient of variation mentioned previously (Burden, 2010; Burden et al., 2003). The finding from the current study that all normalisation methods reduced inter-participant variability for the vastus lateralis compared to unnormalised vastus lateralis EMG is consistent with some previous studies (Burden et al., 2003; Burden and Bartlett, 1999), but not others (Allison et al., 1993; Yang and Winter, 1984). However, the fact that isometric normalisation tasks did not reduce inter-participant variability for the biceps femoris compared to unnormalised EMG is consistent with findings opposing results from the vastus lateralis in the current study (Allison et al., 1993; Yang and Winter, 1984). Researchers who are concerned with inter-participant variability during the back squat exercise in strength-trained individuals should be aware that all normalisation methods employed in the current study reduced variability in comparison to unnormalised EMG for the vastus lateralis, but not the biceps femoris.

2.5 Conclusions

Overall, dynamic EMG normalisation methods for the back squat were demonstrated to be superior compared to maximal isometric methods when considering absolute reliability and sensitivity. Therefore, the 80% of 3RM normalisation method will be employed later in this thesis when comparing neuromuscular and kinetic responses to AEL and CL during the back squat exercise. Additionally, dynamic EMG normalisation methods for the back squat reduced inter-participant variability compared to unnormalised EMG for both muscle actions and muscles. In contrast, maximal isometric methods only reduced inter-participant variability for the biceps femoris. Therefore, researchers conducting studies concerning these three measures should use submaximal dynamic, as opposed to maximal isometric normalisation methods. This finding has important implications for future research as the measurement of vastus lateralis and biceps femoris EMG during the back squat does not have to be confined to facilities equipped with isokinetic dynamometers and also reduces data collection time demands. In order to develop the EMG normalisation literature in future, further research needs to be conducted. Research studies should evaluate the absolute reliability, inter-participant variability, and sensitivity of the EMG of other muscles during the back squat and other key lower-body resistance exercises.

2.6 Recommendations for normalisation method selection

- The 80% of 3RM normalisation method should be used when assessing individual responses or adaptations of vastus lateralis and biceps femoris neuromuscular activation during the concentric and eccentric phases of the back squat exercise.
- The MIS normalisation method should be employed when comparing vastus lateralis and biceps femoris neuromuscular activation between experienced strength-trained individuals during the concentric and eccentric muscle actions of the back squat exercise.
- The 60% or 70% of 3RM normalisation methods should be used when investigating differences in vastus lateralis and biceps femoris neuromuscular activation with increasing loads during the concentric and eccentric phases of the back squat exercise.
- MVC, MIS, or submaximal dynamic normalisation methods can be used when examining vastus lateralis neuromuscular activation inter-participant variability during either the concentric or eccentric phases of the back squat exercise in strength-trained individuals.
- The use of normalisation methods does not reduce biceps femoris inter-participant variability during either the concentric or eccentric phases of the back squat exercise compared to unnormalised EMG.

2.7 Contribution of the chapter to the aims of the thesis

The current chapter addressed the first of the methodological aims of the thesis by evaluating the reliability of maximal isometric and submaximal dynamic EMG normalisation methods for the back squat exercise. The chapter contributed new guidance for researchers measuring EMG during the back squat, as normalisation methods for this particular exercise had not previously been investigated. In order to address the other aims outlined in the first chapter of the thesis the remaining investigations progressed by comparing acute neuromuscular, kinetic, and kinematic responses between AEL and CL, during and after single- and multiple-joint resistance exercise models.

CHAPTER 3

ACUTE NEUROMUSCULAR, KINETIC, AND KINEMATIC RESPONSES TO LOWER-BODY SINGLE-JOINT ACCENTUATED ECCENTRIC LOAD RESISTANCE EXERCISE

Balshaw TG, Chesham RA, Hunter AM.

3.1 Introduction

Before comparing neuromuscular, kinetic, and kinematic responses to AEL and CL in a lower-body multiple-joint free weight exercise model, it was first important to investigate these responses in a simplified single-joint resistance exercise model. This approach was taken in order to reduce technical variation and exercise proficiency issues inherent within multiple-joint free weight resistance exercise. Furthermore, the investigation of single-joint AEL has application for achieving strength gains from cross-education in the contralateral untrained or injured leg (Shima et al., 2002), as well as its use during rehabilitation (Schmitz and Westwood, 2001).

Training interventions comparing AEL and CL have been conducted to assess the efficacy of AEL for enhancing chronic strength adaptations. AEL has been shown to elicit greater strength gains, compared to CL (Norrbrand et al., 2008; Friedmann et al., 2004; Brandenburg and Docherty, 2002; Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000). However, other AEL training intervention studies have demonstrated strength adaptations to equate those seem with CL (Friedmann-Bette et al., 2010; Yarrow et al., 2008; Barstow et al., 2003; Godard et al., 1998; Ben-Sira et al., 1995; Nichols et al., 1995). The ambiguous findings in the existing AEL training interventions make it difficult for practitioners to decide if they should employ this type of resistance exercise with their athletes or clients. Acute multiple-joint free weight lower-body research has previously investigated concentric kinetic variables in order to determine the likely benefits of using AEL on a longitudinal basis (Moore et al., 2007). However, no acute AEL knee extensor research exists investigating physiological responses or manipulating other AEL training programme variables, such as exercise velocity that have previously been reported to effect the nature and magnitude of chronic strength adaptations (Farthing and Chilibeck, 2003a). Therefore, currently there is inadequate information available to practitioners considering employing AEL. Specifically, it is unclear what effect acute AEL has on neuromuscular activation, contractile characteristics, kinetic, and kinematic responses compared to CL.

Determining the acute neuromuscular, contractile characteristic, kinetic, and kinematic responses to single-joint lower-body AEL would inform the prescription or refinement of resistance training programmes for individuals within both athletic and rehabilitative training settings. The results produced from such an investigation would help exercise professionals to decide whether or not to employ AEL with their athletes or patients, during which training phase this back squat variant could be implemented, and how AEL may acutely effect neuromuscular control compared to CL. The primary purpose of the current study was to compare eccentric and concentric phase neuromuscular activation, kinetic, and kinematic responses during AEL and CL in a knee extensor resistance exercise model that has application to exercise-intolerant individuals and those undertaking rehabilitation. The secondary purpose of the study was to investigate the influence of eccentric phase velocity on neuromuscular activation and kinetic outputs during AEL and CL in a knee extensor resistance exercise. The final purpose of the study was to evaluate after-session rate of torque development and contractile characteristic responses between AEL and CL conditions. Tensiomyography provides a non-invasive peripheral measure of contractile characteristics from selected individual muscles (Dahmane et al., 2001; Valencic and Knez, 1997) and has been shown to be stable under a range of different muscle conditions (Ditroilo et al., 2013). Furthermore, tensiomyography can be used to detect changes in contractile function following several different exercise interventions (Hunter et al., 2012; Garcia-Manso et al., 2012; Garcia-Manso et al., 2011). Thus, tensiomyography was employed in the current study to assess contractile characteristic differences between conditions following AEL and CL.

3.2 Methods

3.2.1 Participants

Ten males (aged: 22.2 ± 1.3 years, body mass: 78.4 ± 6.1 kg, height: 1.80 ± 0.06 m, sum of seven skin folds: 62.3 ± 15.0 mm, unilateral 3RM concentric knee extension strength: 119.5 ± 15.0 N.m) with a minimum of 6 months resistance training experience (at least two sessions per week during this time period) participated in the study. Written informed consent was provided by all participants prior to the start of testing, after approval had been granted by the University of Stirling Research Ethics Committee. The principles of the Declaration of Helsinki (2008) were adhered to throughout the study.

3.2.2 Procedures

Unilateral concentric knee extension 3RM

Concentric strength assessments were performed on a Biodex 3 dynamometer with the participant restrained as described in Chapter 2 (section 2.2.3). The lateral femoral epicondyle was aligned with the dynamometer axis and the participant’s dominant leg was strapped to the axis attachment arm above the lateral malleolus. Concentric 3RMs were performed in the isotonic dynamometer mode. In the isotonic setting participants had to overcome the programmed level of torque before movement of the axis leg attachment would occur (Remaud et al., 2005). Increases in torque produced from the knee extensor muscles were absorbed by the dynamometer and resulted in an increase in knee joint angle velocity (Kovaleski et al., 1995). Therefore, the load was essentially constant and velocity varied dependent on the torque exerted by the participant (Power et al., 2010; Remaud et al., 2005). Three incremental load warm-up sets, with decreasing numbers of repetitions (set 1: 10 repetitions, set 2: 5 repetitions and set 3: 3 repetitions), were performed to prepare participants for attempts at establishing their 3RM.

Tensiomyography

Tensiomyography measures were performed with participants seated and restrained in the Biodex 3 dynamometer at a fixed knee joint angle of 70° of flexion (full extension equalling 0°) as described in Chapter 2 (section 2.2.3). Participants remained relaxed with their leg supported whilst tensiomyography measures were conducted. The tensiomyography digital displacement transducer (GK 40, Panoptik d.o.o., Ljubljana, Slovenia) incorporating a spring of 0.17 N/mm^{-1} was mounted to an adaptable tripod and was placed one hand breadth from the superior posterior aspect of the patella (Delagi et al., 1975), perpendicular to the vastus lateralis muscle belly in order to measure radial displacement (Tous-Fajardo et al., 2010). Two 3.2 cm diameter stimulating electrodes (PALS Platinum Neurostimulation Electrodes, Axelgaard Manufacturing Co. Ltd, Denmark) were placed either side of the tensiomyography displacement sensor along the line between the greater trochanter and the lateral femoral epicondyle. The stimulating electrode inferior to the displacement sensor was placed on the vastus lateralis above the muscle-tendon unit. Whereas, the stimulating electrode positioned superior to the displacement sensor was placed ~12 cm above the tip of the displacement sensor. Stimulating electrode and displacement transducer sites were marked with indelible pen to ensure consistent placement across test sessions.

A TMG-S2 unit (TMG-BMC ltd., Ljubljana, Slovenia) was used to electrically stimulate the vastus lateralis with pulses of 1 ms duration at 10 s intervals (Tous-Fajardo et al., 2010). The pulses started at an intensity of 15 mA and increased by 5 mA until maximal displacement increased no further or a stimulus intensity of 110 mA (maximal output) was reached (Tous-Fajardo et al., 2010). The same researcher performed all tensiomyography measures across all test sessions. The researcher who performed the tensiomyography measures had undertaken training with a course provider (Tensiomyography-UK). The tensiomyography stimulator was operated via custom-built software that recorded the rate and magnitude of muscle belly displacement. These measures were used to calculate: (i) vastus lateralis tensiomyography maximal displacement, the maximal muscle displacement upon stimulation (Ditroilo et al., 2011; Tous-Fajardo et al., 2010); and (ii) vastus lateralis tensiomyography contraction time (Figure 3.1), the time it takes the muscle to displace from 10% to 90% of maximal muscle belly displacement (Ditroilo et al., 2011; Tous-Fajardo et al., 2010). Tensiomyography maximal displacement and contraction time were selected as these two variables are considered the most valid tensiomyography measures (Krizaj et al., 2008; Dahmane et al., 2005; Dahmane et al., 2001). The greatest maximal displacement and contraction time obtained during before- and after-intervention measurement time-points were used for analysis purposes.

MVCs

Knee extension MVCs of 2 s duration were completed, with the participant’s dominant leg, to quantify rate of torque development. Participants were seated and secured in the Biodex 3 dynamometer as described for the 3RM test assessment. Rate of torque development was selected as a measure of functional strength given that many daily movements relevant to clinical and athletic populations, such as preventing a fall (Suetta et al., 2004) and sprint running (Aagaard et al., 2002), take less time than required to generate maximal force. Participants were instructed to generate as much force as quickly as possible from the signal to commence the MVC. One-min recovery periods separated MVCs. MVCs were performed at a knee joint flexion angle of 70° (full extension equalling 0°). Torque data from the Biodex 3 dynamometer was

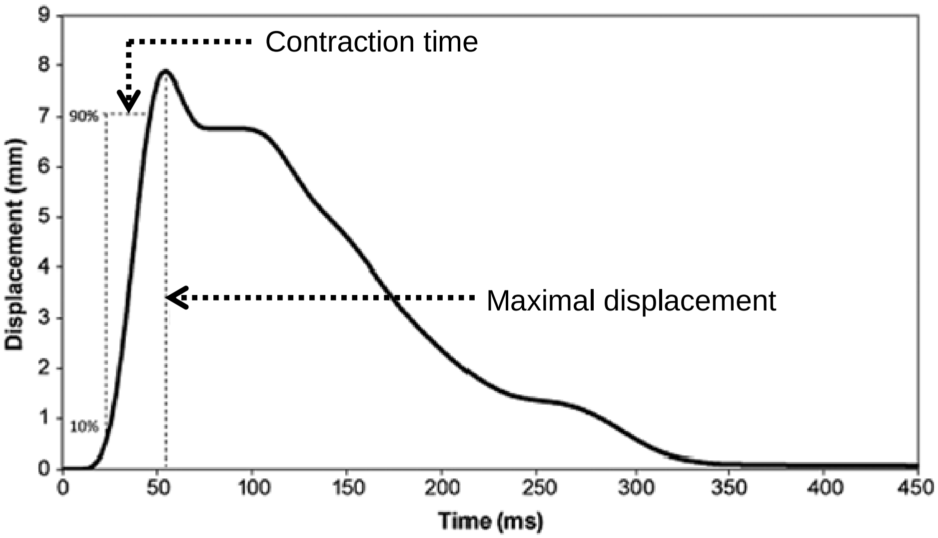


Figure 3.1 Typical tensiomyography displacement/time signal recorded as a result of percutaneous electrical stimulation. Replicated with permission (Ditroilo et al., 2011).

collected during MVCs via integrated hardware (Biopac MP100, Biopac Systems Inc, California, USA) and software (AcqKnowledge® software Version 3.9, Biopac Systems Inc, California, USA) in order to quantify rate of torque development. Rate of torque development was calculated by dividing the change in torque from 0ms to 50 ms, 100 ms, 200 ms, and 300 ms (Δ torque ÷ Δ time) (Aagaard et al., 2002), 0 ms (point of onset) was defined as 5.0% of peak torque obtained during each 2 s MVC (Ditroilo et al., 2011).

3.2.3 Experimental protocol

The study consisted of seven laboratory visits for each participant. The first three visits were used to familiarise participants with knee extension 3RM testing, tensiomyography measures, 2 s MVCs, and experimental condition knee extension efforts. The final four visits involved the completion of four different experimental protocols, conducted in a randomised order, involving the completion of either CL or AEL knee extension efforts (Figure 3.2). A minimum of 5 d separated each experimental test session. In the 48 h prior to reporting for the first experimental test session participants recorded a food and fluid diary. Participants then replicated their

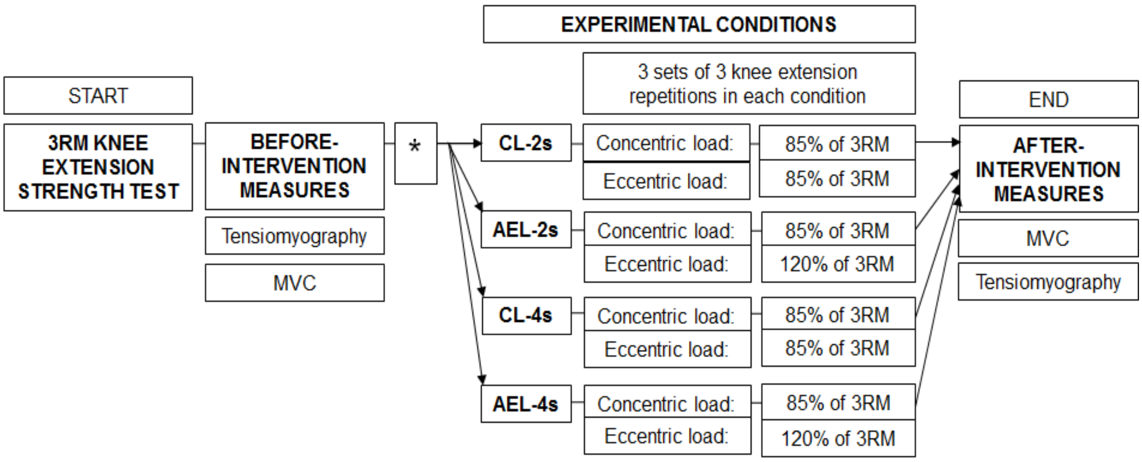


Figure 3.2 Experimental condition protocol. * denotes randomisation of experimental conditions.

dietary intake as closely as possible prior to the final three experimental test sessions. In addition, participants maintained their normal training practices and completed no exercise training in the 24 h prior to reporting for each experimental trial. All testing was conducted following an overnight fast. On arrival at the University laboratory participants were provided with a standardised breakfast (31 kj•kg^{-1} body mass) consisting of 72.5% carbohydrate, 11.9% protein, and 15.7% fat. A 1 h period was taken after the standardised breakfast had been consumed before the experimental testing commenced.

Before either CL or AEL conditions were conducted on each experimental test day unilateral 3RM concentric strength of the participant’s dominant leg was determined. Completion of 3RM assessments during the familiarisation sessions allowed 3RM attempts in experimental test sessions to be limited to a maximum of two or three. This approach was taken in order to prevent the 3RM assessment negatively influencing the performance of the experimental condition knee extension efforts. Absolute reliability of the 3RM across experimental test day sessions was quantified via the calculation of intra-participant coefficient of variation ((SD ÷ mean) × 100) at 3.4%. A 10 min recovery period was taken after the knee extension 3RM, before-intervention vastus lateralis tensiomyography measures and five 2 s MVCs were then performed. One-min recovery periods separated MVCs.

Six min after the 2 s MVCs were completed participants commenced experimental condition knee extension sets. On each experimental test day participants completed one of the following knee extension conditions on the Biodex 3 dynamometer using the same setting as during 3RM assessments: (i) CL with a target 2 s duration eccentric phase (CL-2s); (ii) CL with a target 4 s duration eccentric phase (CL-4s); (iii) AEL with a target 2 s duration eccentric phase (AEL-2s); and (iv) AEL with a target 4 s duration eccentric phase (AEL-4s; Figure 3.2). Participants were seated and secured on the dynamometer during experimental condition sets as described for the knee extension 3RM assessment. Participants performed the eccentric phase of experimental condition repetitions by attempting to match a verbal stop-watch count (of either 2 or 4 s) given by a member of the research team for each repetition. Only the eccentric knee flexion phase velocity was controlled by a verbal count, the concentric knee extension phase was performed as explosively as possible. Participants were instructed to transition as quickly as possible between knee flexion and extension phases and to kick out as explosively as possible for each knee extension repetition. Participant breathing during each experimental condition set involved inspiration during knee flexion and expiration during knee extension. This breathing routine was employed to assist the pacing of the eccentric phase and the explosive nature of the concentric phase (Fleck and Kramer, 2004). Knee extension repetitions were performed through a minimum 70° range of movement, from 90° of knee flexion to 20° of flexion (0° equalling full extension). A minimum 70° range of motion was used given the large decreases in knee extension force production beyond this range (Knapik et al., 1983). The duration of the eccentric phase for each condition was: CL-2s = 1.78 ± 0.27 s, CL-4s = 3.33 ± 0.31 s, AEL-2s = 1.72 ± 0.23 s, AEL-4s = 3.35 ± 0.40 s (mean ± SD).

All experimental conditions consisted of 3 sets of 3 unilateral knee flexion-extension repetitions performed with the dominant leg. Three-min recovery periods were employed between sets. The CL interventions involved loading of 85% of concentric 3RM in both the knee flexion and knee extension phases. AEL interventions involved loading of 120% of concentric 3RM in the knee flexion phase and 85% in the knee extension phase. Work done and time under tension was quantified by the Biodex 3 dynamometer for knee flexion and extension phases in each condition (Table 3.1). Knee extension kinetic and kinematic variables from each experimental set (mean power and peak velocity) were recorded by software integrated with the Biodex 3 dynamometer and stored electronically for later analysis. Three min after the final experimental knee extension set participants completed the first of five after-intervention 2 s MVCs. This time period was selected to avoid transient peripheral potentiation and reduced muscle excitability that has been reported following exercise (Nielsen and de Paoli, 2007; Lentz and Nielsen, 2002). Final tensiomyography measures commenced 3 min after the final after-intervention 2 s MVC. Tensiomyography measures have previously been demonstrated to remain effected in comparison to baseline values for at least 15 min after acute resistance exercise interventions (Garcia-Manso et al., 2012).

3.2.4 EMG

EMG data collection

During experimental condition sets both vastus lateralis and biceps femoris EMG was recorded from the participant’s dominant leg in the same way and using the same equipment as described in Chapter 2 (section 2.2.4). A reference electrode was placed on the lateral malleolus of the participant’s dominant leg and secured with micropore tape. Once electrodes had been positioned in the first experimental intervention test session, electrode sites were marked with an indelible pen. Participants remarked the electrode sites between test sessions to ensure identical

Table 3.1 Work done and time under tension during AEL and CL conditions completed with either a 2 s or 4 s eccentric knee flexion phase.

	Work done (J)						Time under tension (s)					
	Knee flexion			Knee extension			Knee flexion			Knee extension		
Condition	Mean	±	SD	Mean	±	SD	Mean	±	SD	Mean	±	SD
CL-2s	1,765.9	±	308.8	1,671.8	±	217.5	16.0	±	2.4	4.4	±	1.3
AEL-2s	2,285.1	±	534.4	1,659.5	±	252.6	15.5	±	2.1	5.2	±	2.4
Absolute difference	519.2	±	303.7	-12.3	±	76.1	0.7	±	3.8	-0.6	±	2.0
Percentage (%) difference	28.8	±	14.8	-0.9	±	4.5	3.0	±	18.4	-9.8	±	18.6
	Knee flexion			Knee extension			Knee flexion			Knee extension		
Condition	Mean	±	SD	Mean	±	SD	Mean	±	SD	Mean	±	SD
CL-4s	2,151.5	±	348.2	1,769.5	±	263.3	29.9	±	2.7	6.4	±	4.2
AEL-4s	2,667.0	±	344.3	1,708.1	±	207.8	30.1	±	3.6	6.0	±	2.4
Absolute difference	515.5	±	216.7	-61.4	±	131.3	-0.4	±	2.9	0.1	±	3.9
Percentage (%) difference	25.0	±	11.6	-3.0	±	6.6	-1.9	±	15.5	7.8	±	7.1

electrode placement for each testing session. Skin preparation was conducted as detailed in Chapter 2 (section 2.2.4). EMG sampling and filtering was conducted as described iin Chapter 2 (section 2.2.4).

EMG data processing

EMG data was root mean square processed using a 100 ms moving window. Root mean square processing was conducted across the entire waveform for each experimental condition set. EMG processing was completed with the software programme AcqKnowledge® (Version 3.9, Biopac Systems Inc, California, USA) according to manufacturer guidelines (Acqknowledge® software guide, 2008).

Extraction of processed EMG

Once processed, EMG from experimental condition sets was extracted. Eccentric knee flexion and concentric knee extension phase EMG during experimental condition repetitions was extracted based on synchronised dynamometer axis position data, indicating the start and end of each phase. A voltage channel from the Biodex 3 dynamometer quantifying axis position was calibrated, extracted and recorded during experimental condition knee extension sets with integrated AcqKnowledge® software. Mean EMG from both the eccentric knee flexion and concentric knee extension phases of the experimental condition sets were normalised to mean EMG from the corresponding muscle action phase recorded during the heaviest successful 3RM attempt, conducted at the beginning of the respective test session. Experimental condition EMG was normalised to a dynamic exercise task based on recent research and findings from the previous chapter of this thesis advocating the use of dynamic normalisation methods when investigating tasks involving dynamic muscle actions (Albertus-Kajee et al., 2011; Albertus-Kajee et al., 2010).

3.2.5 Statistical analysis

Minitab 16 statistical software (Minitab Ltd., Coventry, UK) was used to conduct all statistical analyses. A time-point (before-intervention vs after-intervention) x condition (CL-2s *vs.* AEL-2s *vs.* CL-4s *vs*. AEL-4s) repeated measures analysis of variance was conducted to assess differences in 2 s MVC rate of torque development and tensiomyography measures. A set (set 1 *vs.* set 2 *vs.* set 3) x condition (CL-2s *vs.* AEL-2s *vs.* CL-4s *vs.* AEL-4s) repeated measures analysis of variance was also conducted to assess statistical differences in EMG, knee extension power and velocity. A significance level of p< 0.05 was selected to determine statistical differences. Tukey *post-hoc* analysis was used where appropriate. All results are expressed as mean ± SD.

3.3 Results

3.3.1 Concentric and eccentric phase EMG during experimental conditions

Greater eccentric vastus lateralis EMG was displayed in the AEL-2s and AEL-4s conditions compared to the CL-2s and CL-4s conditions (p= 0.004, f= 5.73; Figure 3.3 C). Condition-set interaction (p= 0.929, f= 0.31) effects did not occur for eccentric vastus lateralis EMG, but set effects (p= 0.041, f= 3.82) were observed. No condition (p= 0.077, f= 2.55), set (p= 0.354, f= 1.10), or condition-set interaction (p= 0.077, f= 2.55) effects were observed for eccentric biceps femoris EMG. However, both condition and condition-set interaction effects approached significance, with a trend for greater eccentric biceps femoris activation in the AEL-2s condition (Figure 3.3 D). No condition (p= 0.374, f= 1.08), set (p= 0.504, f= 0.71), or condition-set interaction (p= 0.284, f= 1.28) effects were detected for concentric vastus lateralis EMG (Figure 3.3 A). No condition (p= 0.262, f= 1.41), set (p= 0.140, f= 2.20), or condition-set interaction (p=

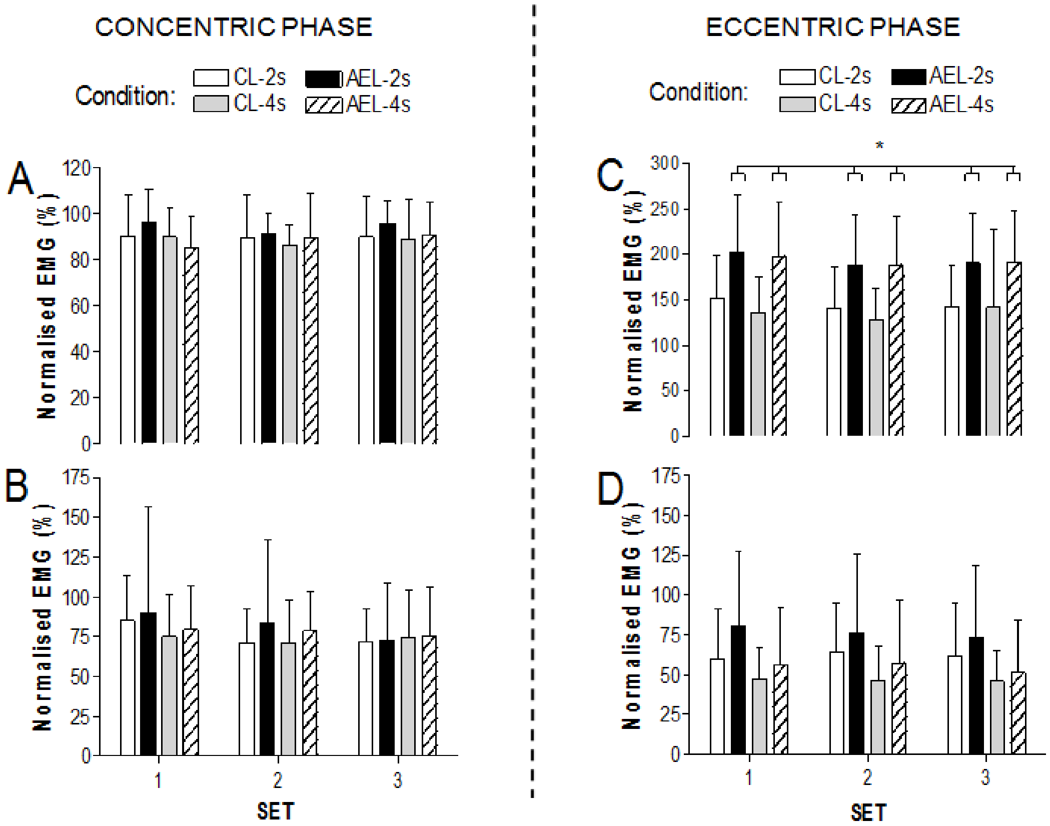


Figure 3.3 Mean vastus lateralis (A,C) and biceps femoris (B,D) EMG during AEL and CL conditions conducted with 2 s or 4 s eccentric knee flexion phases. * denotes greater ($p < 0.05$) eccentric EMG for AEL-2s and AEL-4s conditions compared to corresponding CL conditions.

0.775, f= 0.54) effects were observed for concentric biceps femoris EMG (Figure 3.3 B).

3.3.2 Concentric knee extension kinetic and kinematic variables during experimental conditions

Condition (p= 0.484, f= 0.84), set (p= 0.586, f= 0.55), and condition-set interaction (p= 0.664, f= 0.68) effects were not observed for concentric knee extension power (Figure 3.4 A). Comparisons of concentric peak knee joint angle velocity also did not display condition (p= 0.353, f= 1.13), set (p= 0.466, f= 0.80), or condition-set interaction (p= 0.439, f= 0.99) effects (Figure 3.4 B).

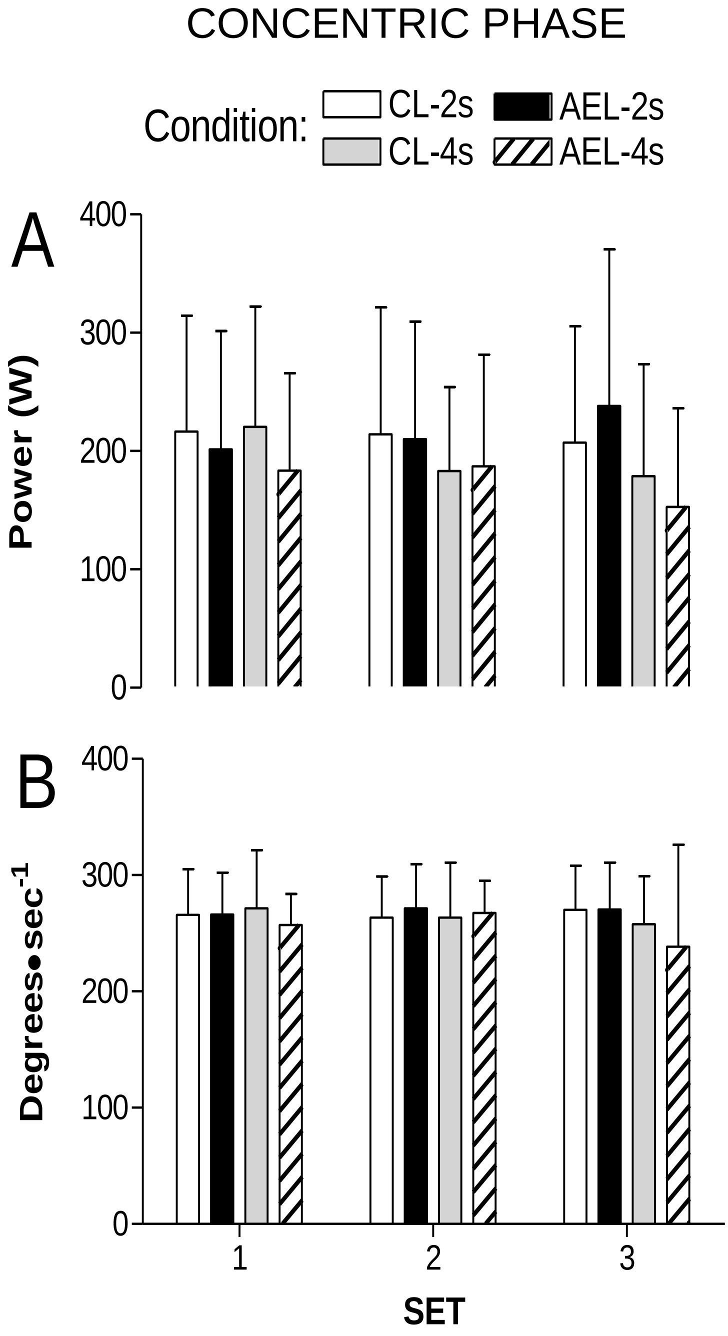


Figure 3.4 Concentric knee extension power (A) and knee joint angle velocity (B) during AEL and CL conditions conducted with 2 s or 4 s eccentric knee flexion phases.

3.3.3 Before- and after-intervention measures

No condition (p= 0.670, f= 0.52), time-point (p= 0.447, f= 0.63), or condition-time-point interaction (p= 0.872, f= 0.23) effects were observed for MVC rate of torque development at 300 ms. As condition, time-point, and condition-time-point interaction effects were also absent for rate of torque development at 50ms, 100ms, or 200ms or 300 ms, only rate of torque development at 300 ms is reported (Figure 3.5 A). Condition (p= 0.621, f= 0.60) and condition-time-point interaction (p= 0.356, f= 1.13) effects did not occur for tensiomyography vastus lateralis contraction time. However, a time-point effect (p= 0.008, f= 11.50) was observed for tensiomyography vastus lateralis contraction time, with a decrease occurring after the intervention compared to before-intervention measures (Figure 3.5 C). No condition (p= 0.520, f= 0.77), time-point (p= 0.639, f= 0.24), or condition-time-point interaction (p= 0.481, f= 0.85) effects occurred for vastus lateralis tensiomyography maximal displacement.

3.4 Discussion

The current study detected elevated eccentric neuromuscular activation for the vastus lateralis during AEL compared to CL, whilst concentric phase vastus lateralis and biceps femoris neuromuscular activation, kinetic, and kinematic outputs were equated between conditions. In addition, a tendency for greater eccentric phase biceps femoris neuromuscular activation was displayed during the faster velocity AEL condition, but not the other conditions. There was a lack of differences in rate of torque development and tensiomyography measures between conditions despite 25.0-29.0% more work being completed in the AEL conditions. The results of the study add novel data to research investigating the efficacy of knee extensor AEL and indicate that there are not any disadvantages of completing acute single-joint knee extensor AEL in terms of neuromuscular function or muscle contractile characteristics. In addition, the effect of other variables such of as exercise velocity during the eccentric phase of AEL had not previously been examined. Therefore, the findings presented provide new physiological

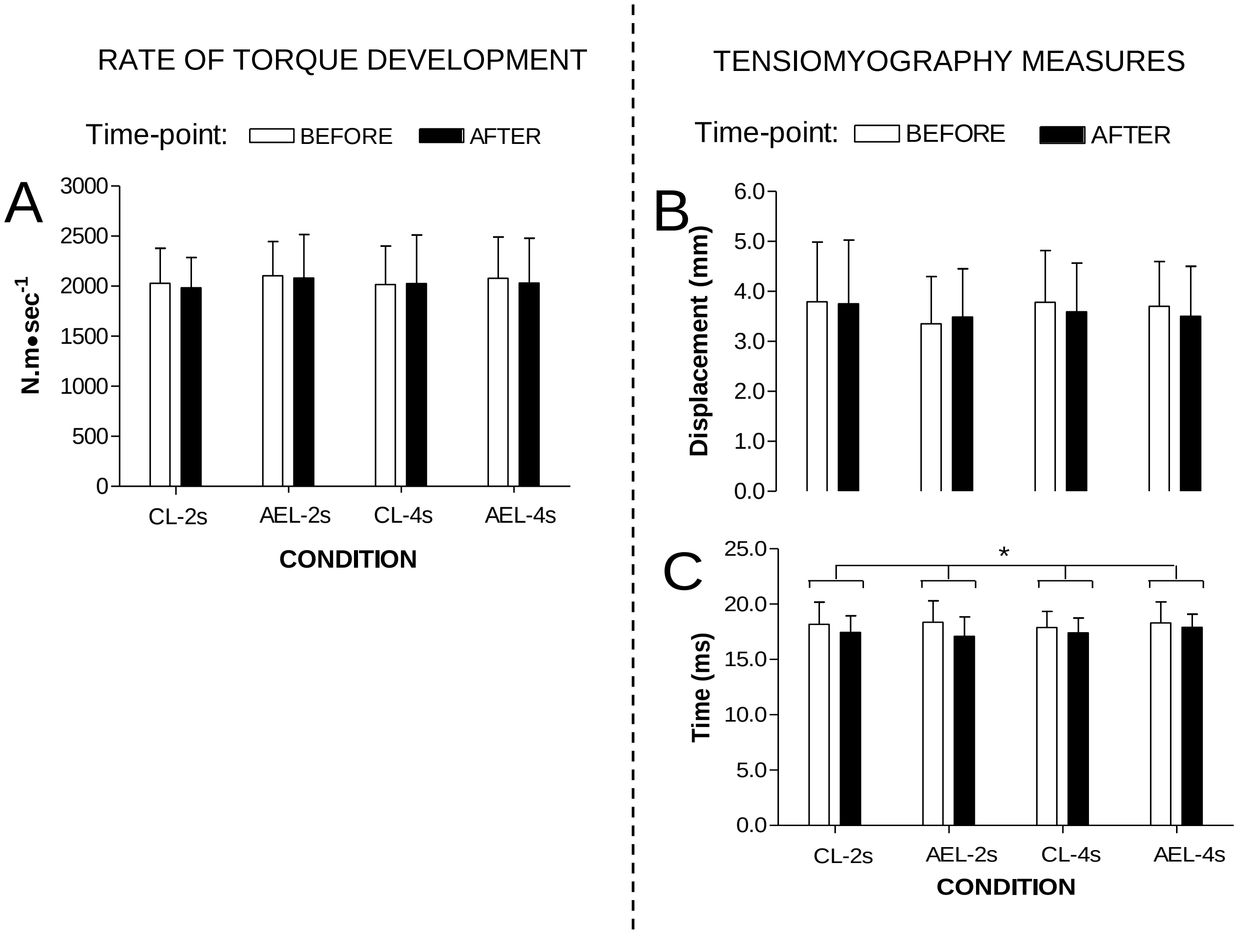


Figure 3.5 Knee extension rate of torque development at 300 ms (A), vastus lateralis tensiomyography maximal displacement (B), and vastus lateralis tensiomyography contraction time (C). * denotes a decrease ($p < 0.05$) in tensiomyography contraction time across conditions from before- to after-intervention measures.

information to guide decisions regarding the efficacy of AEL, the prescription of exercise velocity when employing AEL, and the populations this type of resistance exercise may be suitable for.

The greater vastus lateralis eccentric neuromuscular activation during both AEL conditions was in agreement with previous acute upper-body AEL research which observed elevated agonist eccentric activation (Ojasto and Hakkinen, 2009a; Ojasto and Hakkinen, 2009b). Elevated motor unit firing rates or unique eccentric muscle action recruitment strategies were likely responsible for the greater eccentric neuromuscular activation during the AEL conditions due to the greater eccentric phase torque production required in these conditions (Linnamo et al., 2003). The results presented here are consistent with acute squat-based research where concentric kinetic outputs did not differ between AEL and CL conditions (Moore et al., 2007). In addition, previous research comparing acute concentric neuromuscular responses during AEL and CL in the upper-body musculature also detected no differences between conditions (Ojasto and Hakkinen, 2009a; Ojasto and Hakkinen, 2009b). This body of evidence appears to rule out early hypotheses (Doan et al., 2002) that acute elevated concentric neuromuscular activation may contribute to enhancements in concentric kinetic output during AEL (Ojasto and Hakkinen, 2009a; Doan et al., 2002). The greater eccentric vastus lateralis neuromuscular activation with AEL and equated concentric neuromuscular and concentric kinetic measures between conditions implies AEL may provide an acute training stimulus that over repeated training sessions could develop chronic neuromuscular adaptations of knee extensor muscles during both muscle action phases (Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000; Kaminski et al., 1998). Further research is required to confirm this on a longtidunial basis (e.g. over a 4-12 week duration training intervention).

The manipulation of eccentric phase velocity appeared to influence only antagonist muscle activation during the eccentric phase of repetitions, with a trend for greater BF activation displayed in the AEL-2s condition. This trend for greater biceps femoris eccentric phase neuromuscular activation during AEL-2s compared to the other conditions may have occurred as a response to maintain knee joint stability during a task in which a combination of greater force production and rate of muscle lengthening was required (Gabriel et al., 2006). Exercise velocity did not influence any other variables during knee extension repetitions or after-interventions measures. The fact that rate of torque development and tensiomyography measures were not negatively impacted in the AEL conditions was unexpected, given the greater amount of work completed. Previously, decreased rate of force development, maximal voluntary isometric contraction and peak twitch force had been observed following protocols employing 2 and 4 s eccentric phases during dynamic resistance exercise (Tran et al., 2006). The differences between the present study and this previous study investigating the effect of time under tension likely stem from methodological differences including the way the concentric phase of repetitions were performed, the set and repetition configuration employed, and the muscle group involved (Tran et al., 2006). Vastus lateralis tensiomyography contraction time decreased from before- to after-intervention for both conditions. The alteration in contraction time may be due to small reductions in vastus lateralis muscle fibre pennation angle causing muscle fibre forces to be transmitted more quickly along the length of the muscle (Mahlfeld et al., 2004). However, increases in tendon compliance have also been demonstrated following high force contraction which may explain why increases in after-intervention rate torque development where not found despite the decrease in tensiomyography contraction time (Kubo et al., 2001). The decrease in contraction time at the after-intervention measurement time-point was consistent with research reporting elevated post-resistance exercise tensiomyography contraction velocity (Garcia-Manso et al., 2012), another measure indicative of muscle contraction rate.

Prior to the current study acute AEL research had not assessed after-intervention rate of torque development or contractile characterisitcs. Consequently, there was no indication regarding whether or not this type of resistance exercise would be suitable for athletic or exercise-intolerant populations who may have limited recovery time between training sessions or difficulty performing essential daily tasks. The combined neuromuscular, kinetic, kinematic, and contractile characteristic results of the current study suggest there are not any acute disadvantages to performing AEL in a healthy male recreationally exercising population. Therefore, AEL may be suitable for populations completing concurrent training who are required to develop eccentric strength and could potentially provide a way of accumulating additional exercise volume without compromising mobility or day-to-day function in exercise-intolerant individuals.

3.5 Conclusions

In conclusion, there does not appear to be any disadvantages of completing acute single-joint knee extensor AEL in terms of neuromuscular function or muscle contractile characteristics. Independent of eccentric phase velocity, AEL required elevated eccentric neuromuscular activation, but equated the concentric neuromuscular activation and concentric kinetic and kinematic outputs observed with CL. In addition, despite the AEL conditions involving a greater amount of work after-intervention rate of torque development and vastus lateralis contractile characteristics were not negatively impacted. Therefore, AEL may be a useful training method for populations with a limited capacity to accumulate exercise volume without compromising mobility or thre ability to perform day-to-day tasks. However, longitudinal AEL studies employing eccentric strength assessments and neuromuscular measures are still required to confirm the efficacy of this training method for concurrently enhancing the eccentric and concentric strength of the knee extensor musculature.

3.6 Contribution of the chapter to the aims of the thesis

The current chapter addressed three of the main aims of the thesis. Firstly, by comparing acute neuromuscular, kinetic, and kinematic responses between lower-body single-joint AEL and CL. Secondly, by investigating the influence of eccentric phase velocity on acute neuromuscular, kinetic, and kinematic responses during lower-body single-joint AEL and CL. Thirdly, by assessing after-session rate of torque development and contractile characteristic responses following lower-body single-joint AEL and CL conditions. The findings of the current chapter add novel information to the existing literature, as no research investigating neuromuscular responses to acute knee extensor AEL has been conducted. Furthermore, it was unknown how manipulating training programme variables, such as exercise velocity, would influence acute neuromuscular, kinetic, and kinematic responses during or after AEL. These results are especially pertinent as equivocal reports regarding the efficacy of AEL training interventions make it difficult for practitioners to decide if they should employ AEL. In order to address the remaining aims of the thesis further neuromuscular and kinetic variables were investigated both in single- and multiple-joint resistance exercise models.

CHAPTER 4

ACUTE MOTOR UNIT FIRING RATE AND COMMON DRIVE RESPONSES TO LOWER-BODY SINGLE-JOINT ACCENTUATED ECCENTRIC LOAD RESISTANCE EXERCISE

Balshaw TG, Pahar M, Chesham RA, Graham J, Hunter AM.

4.1 Introduction

To extend the findings of the third chapter of the thesis and provide mechanistic information regarding how AEL may differentially effect acute neuromuscular variables that have been reported to be undergo chronic adaptations, additional measures that were taken before and after the intervention that was described in the previous chapter were analysed. Early responses of the primary motor cortex (Karni et al., 1995; Pascual-Leone et al., 1994) have previously been shown to be involved in human motor learning, with transcranial magnetic stimulation measures used extensively to investigate responses to skill acquisition tasks (Pearce and Kidgell, 2010; Pascual-Leone et al., 1995). The acute neural responses to resistance exercise have previously been likened to motor learning (Lee and Carroll, 2007; Carroll et al., 2001) with motor outputs that produce greater kinetic or kinematic responses during resistance exercise believed to be consolidated by the brain (Carroll et al., 2001). In order to test the hypothesis that favourable kinetic or kinematic outputs are consolidated following resistance exercise, a recent study investigated acute transcranial magnetic stimulation responses to different types of upper-body resistance exercise (Selvanayagam et al., 2011). Consequently, it was confirmed that muscle twitch force vector parameters were altered following single strength and ballistic upper-body resistance exercise sessions (Selvanayagam et al., 2011). This finding supports the association made between resistance exercise and motor learning and also indicates acute neural responses may contribute to chronic strength adaptation outcomes.

AEL has previously been demonstrated to acutely produce greater concentric phase kinetic and kinematic outputs than CL (Sheppard and Young, 2010; Ojasto and Hakkinen, 2009a; Sheppard et al., 2007; Doan et al., 2002). In addition, the greater loading employed during AEL also requires greater force production during the eccentric phase (Reeves et al., 2009; Lastayo et al., 2003b). Furthermore, heavy eccentric-only resistance exercise performed at a fast velocity has been shown to result in greater strength gains compared to equivalent training completed at a slower velocity (Farthing and Chilibeck, 2003b). The greater increase in strength with faster velocity heavy eccentric efforts may be due to the greater acute force levels that are involved in such training (Farthing and Chilibeck, 2003b). Therefore, in accordance with the hypotheses associating neural responses to resistance exercise to those that occur with motor learning (Carroll et al., 2001), faster velocity AEL may have the potential to lead to differential acute neural responses. However, the equivocal strength gains reported in the existing AEL training intervention literature mean it is unclear if AEL leads to enhanced strength adaptations via differential neuromuscular adaptations (Brandenburg and Docherty, 2002; Hortobagyi et al., 2001a; Godard et al., 1998; Kaminski et al., 1998; Ben-Sira et al., 1995; Nichols et al., 1995). This issue is compounded further by the fact that no neuromuscular measures have not been incorporated in AEL training intervention studies that extend beyond intensified 7 d training periods (Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000).

Although transcranial magnetic stimulation has been used previously to investigate both chronic adaptations and acute responses to resistance exercise, the emergence of new hardware and software, namely high density EMG (De Luca et al., 2006), now provides the opportunity to non-invasively procure firing rate data from a high yield of single motor units (Beck et al., 2011; Nawab et al., 2010). Determining how variables such as motor unit firing rate and correlated motor unit activity may be effected in a large number of single lower-body motor units (~40) following resistance exercise may further our current understanding of how acute responses to resistance exercise influence variables that have previously been implicated in chronic neural adaptations (Selvanayagam et al., 2011). This type of research, conducted in the lower-body musculature, may be particularly interesting given the differences in cortical representation between lower-body muscles and the upper-body musculature that has previously been examined via transcranial magnetic stimulation measurements (Selvanayagam et al., 2011).

Motor unit firing rate and common drive are both predominantly regulated centrally but spinal input can also modulate these measures. Intra-muscular wire electrode studies have previously shown motor unit firing rate to increase following acute resistance exercise (Kamen and Knight, 2004; Van Cutsem et al., 1998). In addition, the timing of firings from a motor unit in relation to those of another unit can also reveal acute post-resistance exercise neural adjustments (De Luca et al., 2006). For example, cross-correlation analysis of motor unit firing rate, dependent on the pre-filtering technique applied (Negro and Farina, 2012), can be used to quantify different variables (Datta and Stephens, 1990), such as common drive (De Luca et al., 1982). Common drive is calculated from mean motor unit firing rate data and represents simultaneous fluctuations in firing rate between pairs of motor units (De Luca et al., 1982).

Cross-sectional studies have reported greater common drive in strength-trained compared to skill-trained individuals (Semmler and Nordstrom, 1998), suggesting increases in common drive may be implicated in the neuromuscular adaptations responsible for increases in chronic strength levels. In contrast, other cross-sectional research has suggested no differences in common drive exist between skill-, endurance-, and strength-trained individuals (De Luca et al., 1982). These studies have employed fine wire electrodes in order to obtain individual motor unit firing rate data, as a result cross-correlation analysis was restricted to a limited number of motor units from each differentially trained population (Semmler and Nordstrom, 1998). The use of high density EMG measures negates issues associated with small motor unit yields and permits what may be considered a more sensitive measure of common drive (Carroll et al., 2011). In addition, high density EMG can allow the assessment of motor unit firing rates from distinct motor unit populations that are recruited at differential force levels (earlier-recruited and later-recruited motor units) to be assessed. AEL has previously been shown to increase the CSA of type IIX, but not other muscle fibre types. Whether, different acute neural responses occur between separate motor unit populations in a similar way to the reported morphological adaptations following AEL is unknown. The comparison of acute motor unit firing rate and common drive responses to AEL and CL, determined via high density EMG, may support or dismiss the use of AEL for bringing about superior chronic strength adaptations. Therefore, the purposes of the study were twofold; firstly, to compare motor unit firing rate and common drive responses after lower-body single-joint AEL and CL; and secondly, to assess the between-day reliability and inter-participant variability of motor unit firing rate analysis during a submaximal lower-body isometric trapezoid force trace effort.

4.2 Methods

4.2.1 Participants

The same ten males who were described in Chapter 3 (section 3.2.1) completed the additional neuromuscular measurements detailed within this chapter.

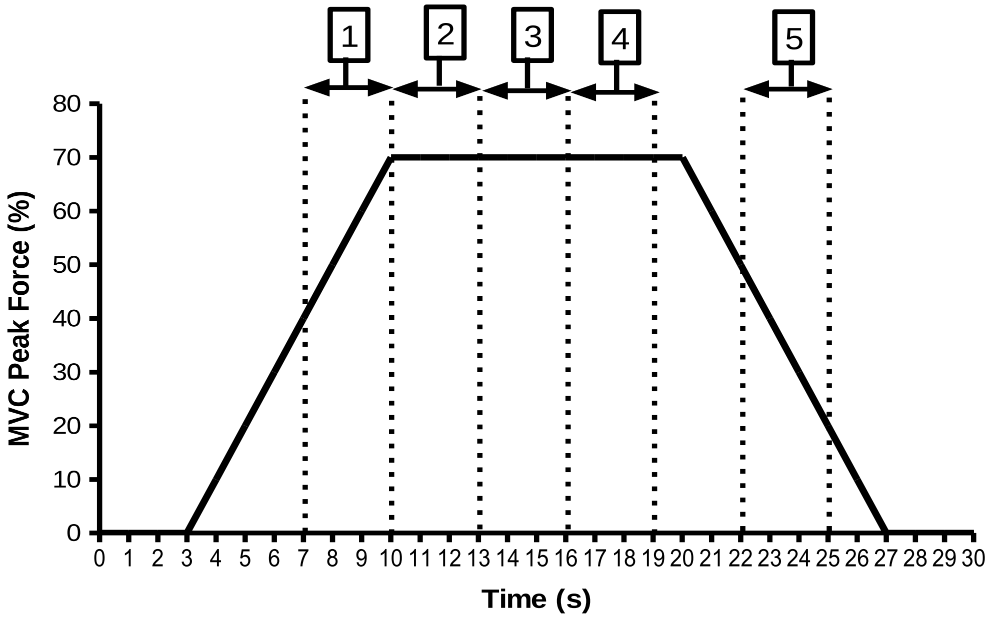


Figure 4.1 Knee extension isometric trapezoid effort force trace (denoted as a percentage of MVC peak force) with illustration of the identified time periods that were used for motor unit firing rate analysis: (1) ascent or recruitment phase; (2-4) plateau or constant force phase; and (5) descent or derecruitment phase.

4.2.2 Procedures

Isometric trapezoid force trace

Isometric trapezoid knee extension force trace efforts involved a 3 s quiescent period, a linear 7 s ramp-up in force from 0% to 70% of before-intervention peak MVC force, a 10 s holding force levels constant at 70% of peak MVC force, a linear 7 s ramp-down from 70% to 0% of MVC peak force, and a final 3 s quiescent period (Figure 4.1). Isometric trapezoid efforts were performed at a knee joint flexion angle of 70° (full extension equalling 0°). Participants met the required isometric trapezoid force trace via visual feedback displayed on a computer screen positioned in front of them at eye level. The majority of studies performing cross-correlation analysis of single motor units have employed force levels ≤30% of MVC (Fling et al., 2009). Therefore, findings have been limited to motor units recruited at these low force levels. As the AEL and CL interventions investigated throughout this thesis involved high force levels it was critical to investigate motor unit firing rate and common drive responses at as high an isometric force level that could be maintained for the duration of the 10 s plateau phase. The selection of greater isometric force during the trapezoid force trace efforts would permit the effect of the AEL and CL interventions on a larger range of motor units to be assessed.

4.2.3 Experimental protocol

The same experimental protocol as detailed in Chapter 3 was completed by participants (Figure 4.2). The initial three sessions were used to familiarise participants with the tasks to be performed in the four final experimental condition testing sessions. A minimum of 5 d separated each experimental test day. In addition to the familiarisation tasks listed in Chapter 3 (section 3.2.3) participants were also familiarised with the performance of 5 s knee extension MVCs and isometric knee extension trapezoid force trace efforts. All isometric knee extension efforts were performed with the participant’s dominant leg whilst they were seated and secured on a Biodex 3 dynamometer as described in Chapter 2 (section 2.2.2).

The control of variables before experimental testing sessions was the same as that detailed in Chapter 3 (section 3.2.3). 3RM knee extension strength was assessed at the beginning of each test day as described in Chapter 3 (section 3.2.2). Fifteen min after the knee extension 3RM, before-intervention MVC and isometric trapezoid force trace efforts were performed. A single 5 s MVC was performed followed by a single isometric trapezoid force trace effort. The 5 s MVCs performed before- and after-experimental interventions were conducted as described in Chapter 2 (section 2.2.2). The absolute reliability of 5 s MVC peak force had previously been established at 8.0% in Chapter 2 (section 2.3.1). One min recovery periods separated MVC and isometric force trace efforts. Eight min after knee extension repetitions had been completed in each experimental condition after-intervention MVC and isometric trapezoid efforts were completed.

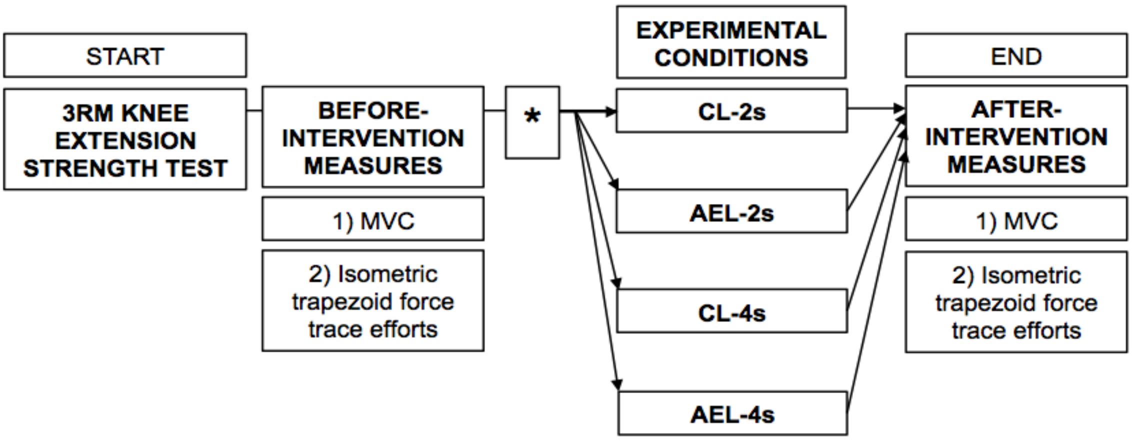


Figure 4.2 Experimental condition protocol. * denotes randomisation of experimental conditions.

A 3 min rest period was taken following isometric trapezoid force trace efforts before experimental condition knee extension sets were completed. One of the four knee extension conditions described in Chapter 3 (section 3.2.3) was completed on each test day (CL-2s, CL-4s, AEL-2s, or AEL-4s). The duration of the eccentric phase in each condition was as described in the previous chapter (section 3.2.3).

4.2.4 High density EMG and MVC force data collection

Vastus lateralis high density EMG was measured and amplified during the isometric force trace efforts with the use of a modified Bagnoli 16-channel EMG system (Delsys, Boston, USA). A five pin sensor was applied to the vastus lateralis between the site recommended by Surface Electromyography for the Non-Invasive Assessment of Muscles guidelines guidelines for vastus lateralis bipolar surface electrode configuration and the belly of the vastus lateralis (Figure 4.3 A). High density EMG electrode placement was adjusted to ensure a minimum 4:1 signal to noise ratio was obtained before commencing measurements. The sensor consisted of five cylindrical blunted probes, each with a diameter of 0.5 mm. The probes occupied the four corners and the centre of a 5 x 5 mm square (Figure 4.3 B). The sensor was pressed forcefully in to the skin whilst avoiding piercing of the skin and was secured with micropore tape. Before placing and securing the electrode, skin preparation was conducted as detailed in Chapter 2 (section 2.2.4). A 5.08 cm diameter reference electrode (HE-R, Dermatrode, American Imex, Irvine) was applied to the patella of the participant’s involved leg. The high density EMG system recorded four separate bipolar EMG signals from the five-pin sensor probe array at a sampling frequency of 20 kHZ. The four signals from each isometric trapezoid force trace effort were filtered with a band width of 20 to 1750 Hz (De Luca and Contessa, 2012). Vastus lateralis high density EMG and force data from the Biodex 3 dynamometer were synchronously recorded via software (EMGworks® 4.0 Acquisition software, Delsys, Boston, USA) integrated with the high density EMG system. Voltage data measured from the Biodex 3 was calibrated within the EMGworks® software during the dynamometer calibration to allow force data to be captured during MVC and isometric trapezoid force trace efforts.

4.2.5 EMG signal decomposition, analysis, and accuracy

High density EMG signal decomposition

Vastus lateralis high density EMG motor unit firing rate, common drive, and MVC force data were processed with EMGworks® 4.0 Analysis software (Delsys, Boston, USA). In addition Matlab software (Mathworks, Inc., Natick, USA) was used to produce absolute motor unit firing rate data from each of the identified time periods during the isometric trapezoid force trace efforts (Figure 4.1). In order to decompose surface EMG collected with the high density EMG system into constituent motor unit action potential trains, Precision Decomposition III algorithms were used (De Luca et al., 2006). These algorithms employ the artificial intelligence framework known as “Integrated Processing and Understanding of Signals” in order to separate the action potentials of different motor units from the overall surface EMG signal. The Precision Decomposition III

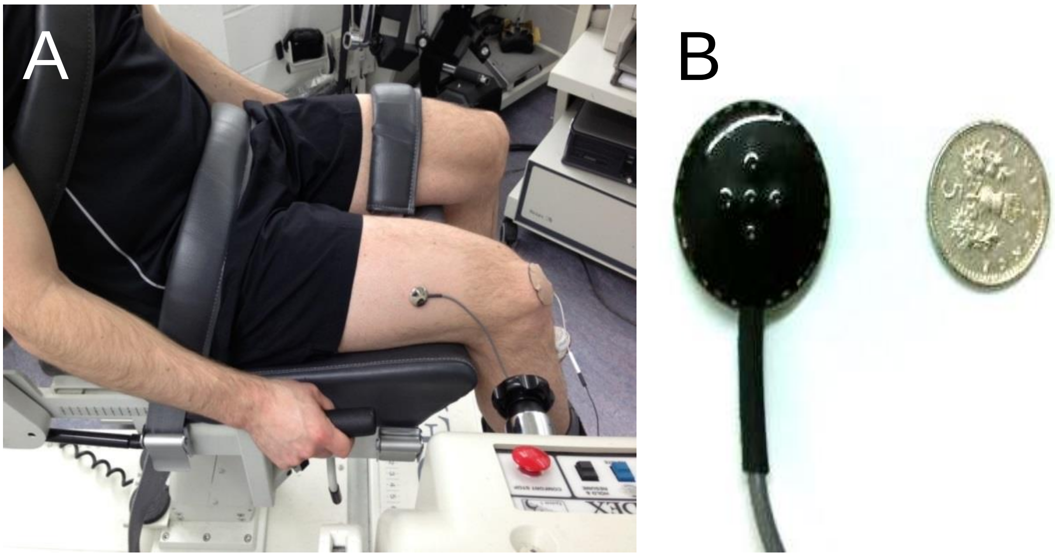


Figure 4.3 The five-pin high density EMG sensor applied to the vastus lateralis before being secured with micropore tape (A) and next to a 5 pence coin included for size reference (B). The pins on the corners of the square are spaced 5 mm apart.

system involves four separate stages that takes the surface EMG signal input ($x(t)$) and produces motor unit action potential trains of the individual motor units ($y^{(j)}(t)$, j= 1, 2,..., *N*) identified within the input signal (Figure 4.4).

Stage 1: The input signal is filtered with an 8th order Butterworth digital IIR band-pass filter (lower cut-off: 24 dB/octave <250 Hz; upper cut-off: 24 dB/octave >2,000 Hz).

Stage 2: During the second phase of the Precision Decomposition III system a segmented version of the filtered input signal is passed through a maximum a posteriori probability receiver (LeFever and De Luca, 1982). Segments of the filtered input signal are determined based on signal amplitude in relation to dynamic range criteria for the amplitudes of decomposable motor unit trains. These segments then contribute to the construction of motor unit action potential train templates for each hypothesised motor unit. The maximum a posteriori probability receiver subsequently classifies characteristics of the segmented signal based on amplitude peaks and associates a hypothesised motor unit. Specifically, the maximum a posteriori probability receiver assigns a component of the segmented signal to a particular motor unit and

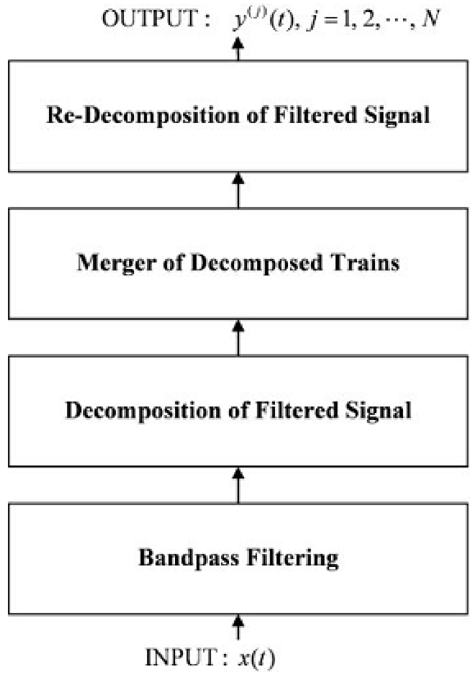


Figure 4.4 Block diagram of the main components of the Precision Decomposition III algorithms. Replicated with permission (De Luca et al., 2006).

the probability that the motor unit the signal component has been distributed to belong to the motor unit's pulse train is then assessed by a hazard function (LeFever and De Luca, 1982). Finally, signal segments are assessed in relation to existing motor units and if the maximum a posteriori probability does not determine a match between units a new motor unit template is added. However, If a match is determined between a signal segment and an existing motor unit template the existing motor unit is updated using a recursive relation formula.

Stage 3. The third phase of the Precision Decomposition III algorithm assesses the probability that the motor unit action potential trains of a single motor unit have been split into two or more separate motor units using a "trellis traversal" search strategy (Castanon, 1990). This strategy also merges trains with a high probability of belonging to the same motor unit. The probability separate trains belong to the same motor unit is assessed through the level of correlation between trains and how uncorrelated they are to other motor unit action potential trains.

Stage 4. The final stage of the Precision Decomposition III system reanalyses “degenerate” motor unit trains in which interference between two or more action potentials results in the maximum a posteriori probability receiver classifying the signal segment as belonging to a new motor unit, without finding a matching action potential later in the signal. The reanalysis conducted in phase four identifies non-degenerate trains from the maximum a posteriori probability receiver that are consistent with the data in overlapping regions. This process involves the identification of the maximal amplitude motor unit and the points the maximal amplitude motor unit’s local peak cross-correlation is greater in relation to that of the other motor units. This process allows the probability that the maximal amplitude motor unit’s action potential actually occurred at the identified point. A probability threshold is established from the maximum probability level produced following correlation of the maximal amplitude template with all other motor unit templates. At the points where the probability that the identified action potential belongs to the maximal amplitude motor unit exceeds the probability threshold, a scaled version of the template of the maximal amplitude motor unit is removed from the surface EMG signal. This process is repeated with the identification of a new maximal amplitude motor unit following removal of the previous maximal amplitude motor unit template. Once this process has been completed for all motor units, the correlation results undergo a utility maximisation process (Von Neumann and Morgenstern, 1944) allowing decisions to be made regarding which motor unit action potential trains are consistent with the overlapping data.

Firing rate and motor unit number analysis

The firing rate of motor units from the decomposed high density EMG signals were analysed by dividing the motor units by order of recruitment into three separate groups (or tertiles): (i) earlier-recruited; (ii) mid-recruited; and (iii) later-recruited motor units (Figure 4.5). The three separate groups were formed by arbitrarily dividing the total number of motor units by three, if a number of motor units that did not divide

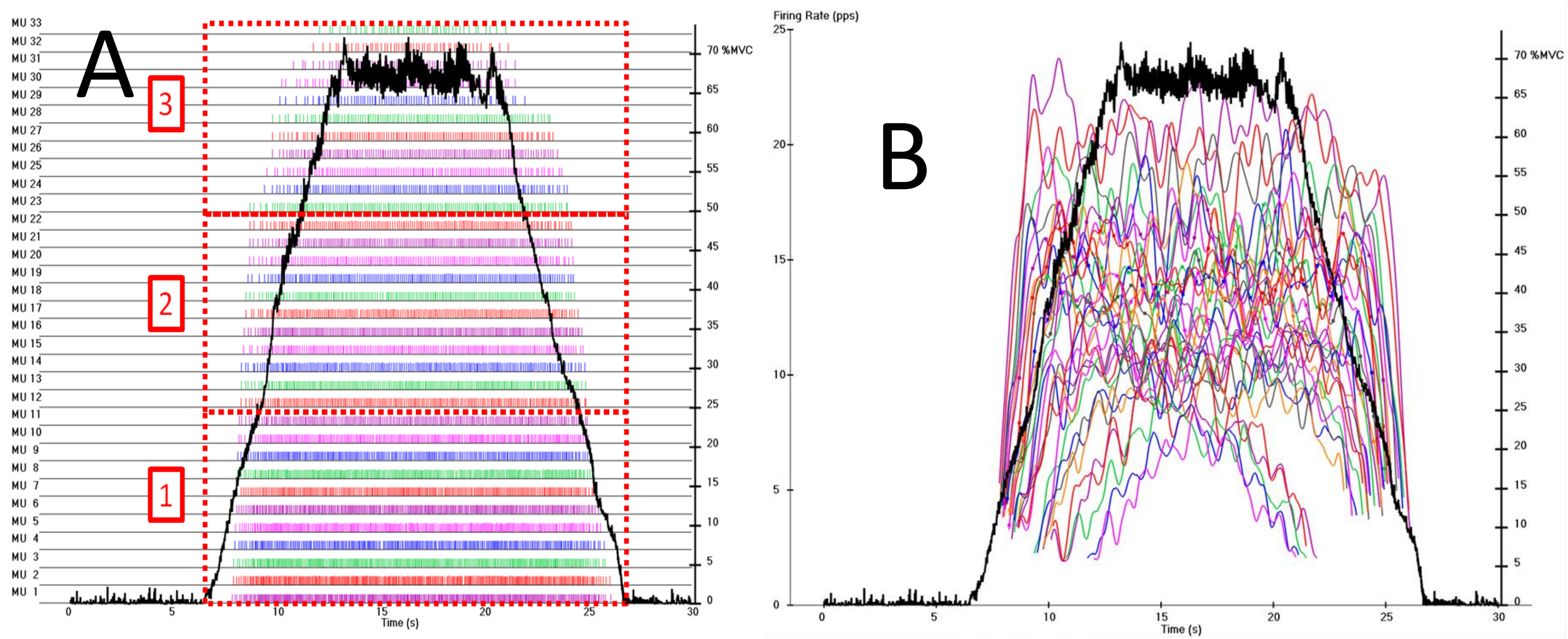


Figure 4.5 Firing rate bar plot (A) and mean firing rate curve plot (B) of one participant. Vertical lines on the firing rate bar plot represent the firings of each motor unit and each individual curve on the firing rate curve plot represents the mean firing rate of a single detected motor unit (B). The black line indicates the force trace produced by the participant as a percentage of knee extension MVC. The red broken line boxes denote the three identified motor unit populations used for analysis; 1.) earlier-recruited; 2.) mid-recruited; and 3.) later-recruited motor units.

evenly by three was detected additional motor units were added to the later-recruited motor unit group. For example if 34 motor units were detected the earlier-recruited and mid-recruited motor unit would have 11 motor units in each group, whereas the later-recruited motor units would have 12 motor units. This allowed the analysis of three populations of motor units which were expected to display differential firing rate characteristics (Eccles et al., 1958). Specific 3 s time periods during the isometric trapezoid force trace were analysed to provide details of firing rate of each of the three motor unit populations during the: (i) ascent; (ii) plateau; and (iii) descent portions of the isometric trapezoid force trace efforts (Figure 4.1). In addition, the reliability of motor unit firing rate during the identified 3 s time periods was investigated during before-intervention isometric trapezoid force trace efforts. Motor unit firing rate reliability was assessed to determine the suitability of using each section of the trapezoid for analysis. The maximum number of motor units detected during each isometric trapezoid force trace effort was also compared between conditions.

Common drive

Common drive was analysed using the EMGworks® 4.0 Analysis software. In order to quantify common drive, constituent motor unit action potential trains were converted to motor unit firing rate curves after being smoothed with an 800 ms Hanning window filter. Motor unit firing rate curves for all unique pairs of motor units were then cross-correlated during the time period of the constant force part of the isometric force trace effort (Figure 4.1; t_1= start of selected constant force region, t_2= end of selected constant force region) which displayed the greatest absolute reliability for motor unit firing rate. During this period of constant force correlations between firing rates are not expected to result from variation in the force generated by the involved muscle. The two input series (R_1 and R_2) from each unique pairing of motor units were filtered with an 8th order high pass Butterworth filter with a cut-off of 0.75 Hz to produce $R_{1\ \mathrm{filt}}$ and $R_{2\ \mathrm{filt}}$. $R_{1\ \mathrm{filt}}$ and $R_{2\ \mathrm{filt}}$ were then subsetted to the region of interest (t_1 to t_2) producing $R_{1\ \mathrm{sub}}$

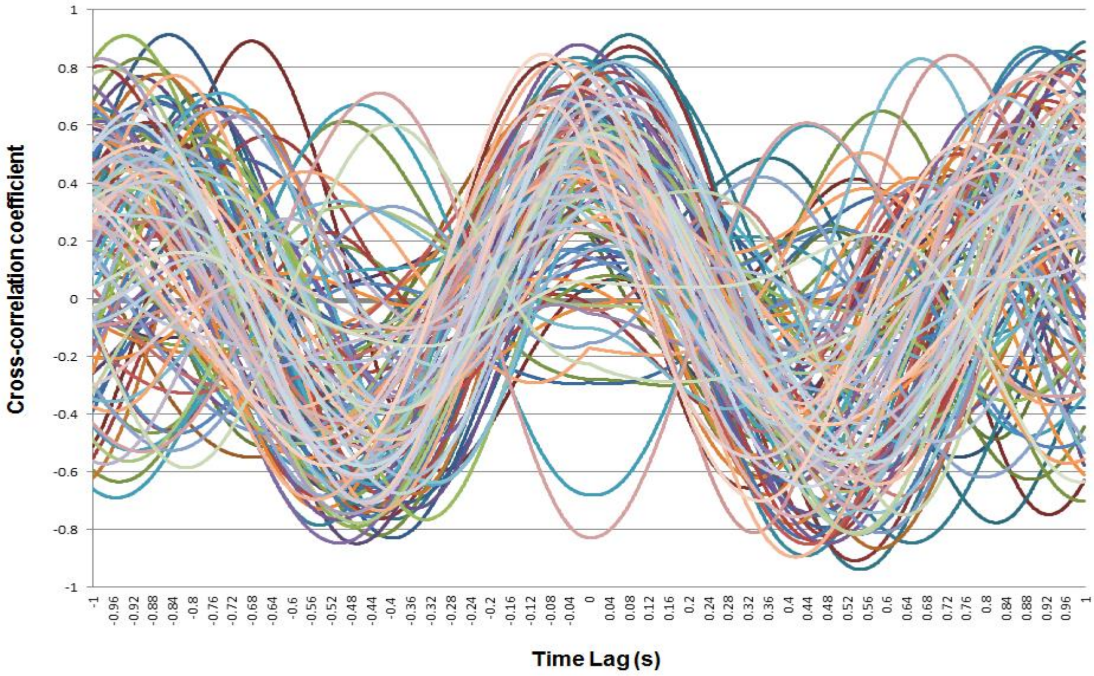


Figure 4.6 Cross-correlation coefficient function output for a single time-point for one participant during the study. Each curve displayed on the figure represents the output of the cross-correlation between two motor unit mean firing rate curves in which peak cross-correlation coefficients occurred within the specified constant force time period of the isometric trapezoid force trace effort. Maximum and mean peak cross-correlation results were obtained from these coefficient function outputs.

and $R_{2\ sub}$. The normalised cross-correlation was computed between $R_{1\ sub}$ and $R_{2\ sub}$ with up to a 1 s time-lag (Figure 4.6). Pairs of motor units in which peak cross-correlation coefficients occurred within the specified constant force time period of the isometric trapezoid force trace effort were included within the analysis. In keeping with recent research conducting common drive analysis all potential combinations of motor unit pairs were cross-correlated with each other (Beck et al., 2012). Therefore, if 20 motor units were detected, from the number of unique combinations of motor unit pairs, up to 190 maximum peak cross-correlation values could be included within the analysis. The maximum peak cross-correlation value that was obtained across each unique pair of motor units that were cross-correlated was used for analysis. In addition, the mean of the peak cross-correlations obtained across reference motor units was also used for analysis. Frequency histograms of the peak cross-correlation coefficients achieved from each unique pair of motor units that were cross-correlated across all participants were plotted, in order to provide further assessment of common drive responses (Beck et al., 2012).

Decomposition accuracy

The accuracy of the decomposition for each isometric trapezoid force trace effort conducted was assessed with “reconstruct and test” analysis (Figure 4.7;(De Luca and Contessa, 2012; Nawab et al., 2010). The “reconstruct and test” analysis (Nawab et al., 2010) is currently considered the most suitable way of validating the decomposition of high density EMG signals (De Luca and Nawab, 2011). This analysis (Accuracy = 1 - N_{error}/N_{truth} (Where N_{error} is the total number of unmatched events, and N_{truth} is the total number of true events)) assesses the level of firing rate accuracy of each detected motor unit and the number of errors•s^{-1}, across the entire duration of the submaximal isometric trapezoid force trace effort. Each detected motor unit was required to display an accuracy level of >85.0% across the entire isometric trapezoid force trace effort in order to be included for analysis (Stock et al., 2012). Accuracy levels during the plateau phase of the isometric trapezoid force trace efforts were typically >92.5%.

4.2.6 Statistical analysis

Minitab 16 statistical software (Minitab Ltd., Coventry, UK) was used to conduct all statistical analysis. The normality of force data and high density EMG variables were assessed via Q-Q plots and constant variance, subsequently normality of the data was confirmed. A time-point (before-intervention *vs.* after-intervention) x condition (CL-2s *vs.* AEL-2s *vs.* CL-4s *vs.* AEL-4s) repeated measures analysis of variance was conducted to assess differences in firing rate, the maximum number of detected motor units, cross-correlation coefficients, and MVC peak force between conditions. A significance level of $p < 0.05$ was selected to determine statistical differences. Tukey

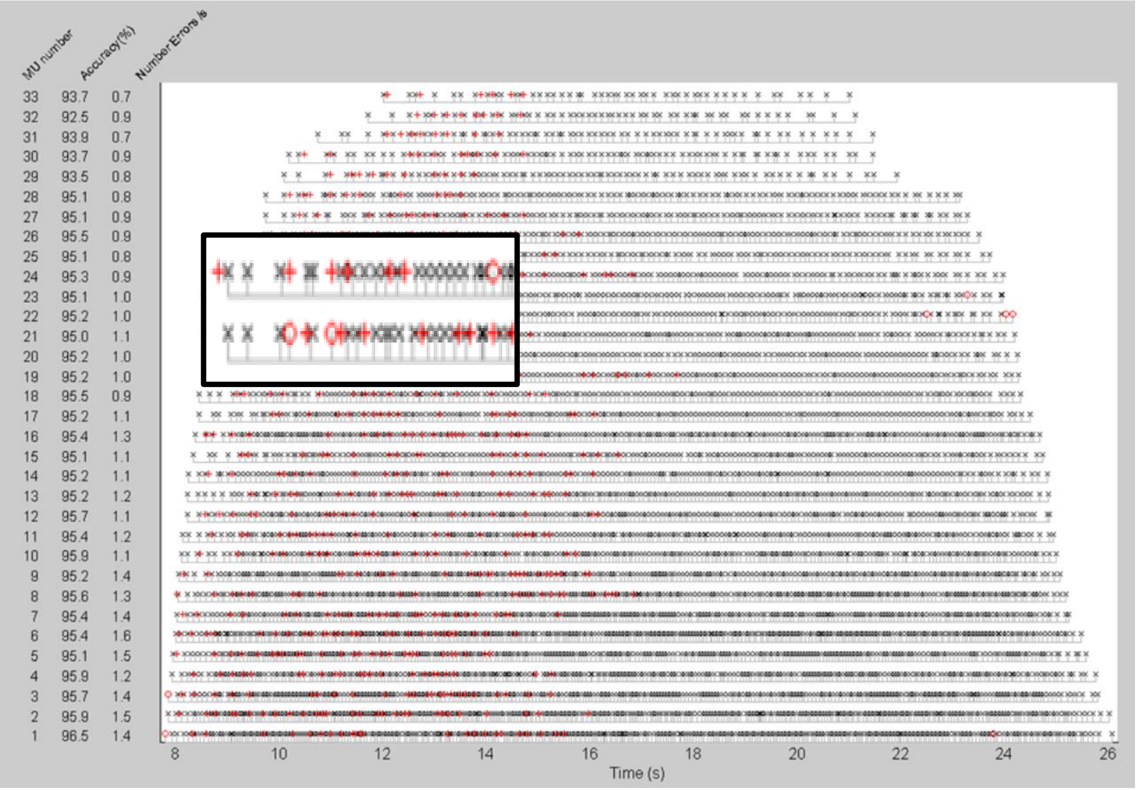


Figure 4.7 Reconstruct and test analysis output used to determine decomposition accuracy for one participant’s knee extension isometric trapezoid force trace effort. Motor unit number, accuracy rate, and number of errors•s^{-1} are displayed on the left side of the figure. Vertical spikes on the figure represent each motor unit firing, firings with a circle denote a false positive, and firings with crosses denote a false negative.

post-hoc analysis was used to determine where differences occurred between loading conditions.

Absolute and relative reliability, as well as inter-participant variability (all defined in Chapter 2 (section 2.2.5)) of firing rate data were calculated for each motor unit population (earlier-recruited, mid-recruited, and later-recruited) during the five identified time periods (Figure 4.1) of before-intervention isometric trapezoid force trace efforts on each experimental test day. Absolute reliability of motor unit firing rate data was assessed via intra-participant coefficient of variation and limits of agreement. Intra-participant coefficent of variation standards were adopted from previous electromyography research and were defined as follows: <12.0%= “good”, 12.0-20%= “acceptable”, >20.0%= “unacceptable” (Albertus-Kajee et al., 2010). Relative reliability of motor unit firing rate data was assessed using intraclass correlation coefficients. Intraclass correlation coefficient values and 95% confidence intervals were calculated with statistical spreadsheets downloaded from www.sportsci.org (Hopkins, 2010). Intraclass correlation coefficient variation were adopted from a recent neuromuscular physiology reliability study and were defined as follows: 0.80–1.00= “excellent”, 0.60–0.80= “good”, and <0.60= “poor” (Buckthorpe et al., 2012). Inter-participant variability of motor unit firing rate data was assessed using inter-participant coefficient of variation in order to determine if “common” firing rates existed between participants.

4.3 Results

4.3.1 Motor unit firing rate, number of detected motor units, and MVC force

Time phase four, from the plateau phase of the isometric trapezoid force trace effort, demonstrated the greatest absolute reliability across the largest number of motor unit firing rate tertiles. The other time phases typically showed lower absolute reliability (>12.0% coefficient of variation). Given the greater absolute reliability of time phase four this period alone was used for motor unit firing rate analysis. No condition effects were detected for firing rate in earlier-recruited (p= 0.092, f= 2.37), mid-recruited (p= 0.159, f= 1.87), or later-recruited (p= 0.136, f= 2.01) motor unit populations (Figure 4.8). No time effects were observed for firing rate in earlier-recruited (p= 0.284, f= 1.30), mid-recruited (p= 0.126, f= 2.84), or later-recruited (p= 0.964, f= 0.00) motor unit populations. A condition-time-point interaction effect was observed for the later-recruited (p= 0.025, f= 3.65) motor units, but not earlier-recruited (p= 0.286, f= 1.33) or mid-recruited (p= 0.399, f= 1.02) units. The condition-time-point interaction effect in the later-recruited motor unit population revealed a decrease in motor unit firing rate from before- to after-intervention measures in the AEL-2s condition (Figure 4.8 C). No differences in the maximum number of detected motor units were observed between conditions (p= 0.989, f= 0.04; Figure 4.9 A). Additionally, no time-point (p= 0.713, f= 0.14) or condition-time-point interaction (p= 0.139, f= 1.99) effects were observed for the maximum number of detected motor units. MVC peak force demonstrated no condition (p= 0.446, f= 0.92), time-point (p= 0.282, f= 10.01), or condition-time-point interaction (p= 0.896, f= 0.20) effects (Figure 4.9 B).

4.3.2 Common drive

Due to processing difficulties an *n* of 9 was included for common drive analyses. As time phase four of the isometric trapezoid force trace efforts demonstrated the greatest absolute reliability across the largest number of motor unit populations this plateau phase alone was used for common drive analysis. No differences between conditions were shown in common drive, as displayed by frequency histogram analysis (Figure 4.10), maximum (p= 0.678, f= 0.51; Figure 4.11 A) and mean (p= 0.873, f= 0.23; Figure 4.11 B) peak cross-correlation coefficient values. Time-point effects were not detected for maximum (p= 0.981, f= 0.00) or mean (p= 0.692, f= 0.17) peak cross-correlation coefficient values. Condition-time-point interaction effects were not observed for maximum (p= 0.696, f= 0.48) or mean (p= 0.953, f= 0.11) peak cross-correlation coefficient values.

4.3.3 Decomposition accuracy

Before-intervention isometric trapezoid force trace efforts displayed 94.4 ± 2.5%, 95.5 ± 1.5%, 93.7 ± 2.3%, and 92.7 ± 2.6% accuracy across the duration of the entire isometric trapezoid force trace effort in the CL-2s, AEL-2s, CL-4s, and AEL-4s conditions, respectively. After-intervention isometric trapezoid force trace efforts displayed 93.6 ± 2.4%, 93.2 ± 3.3%, 92.4 ± 2.6%, and 93.1 ± 2.7% accuracy across the duration of the entire trapezoid effort in the CL-2s, AEL-2s, CL-4s, and AEL-4s conditions, respectively. Before-intervention isometric trapezoid force trace efforts demonstrated 1.3 ± 0.6 errors•s^{-1}, 1.0 ± 0.3 errors•s^{-1}, 1.3 ± 0.4 errors•s^{-1}, and 1.6 ± 0.4 errors•s^{-1} across the duration of the entire isometric trapezoid force trace effort in the

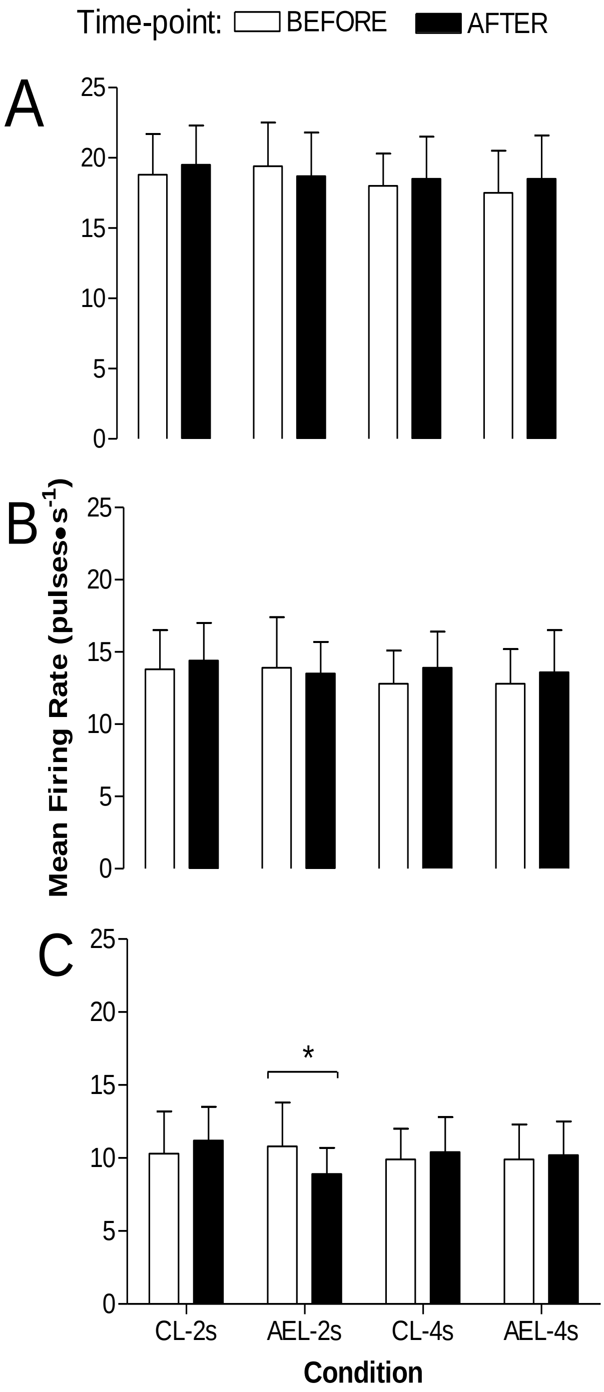


Figure 4.8 Mean vastus lateralis firing rate (pulses•s^{-1}) during the selected region of the constant force phase of the isometric trapezoid force trace effort for: (A) earlier-recruited; (B) mid-recruited; and (C) later-recruited motor units during AEL and CL conditions conducted with either a 2 s or 4 s eccentric knee flexion phase. * denotes a decrease ($p < 0.05$) in firing rate from before to after intervention measures in the AEL-2s condition.

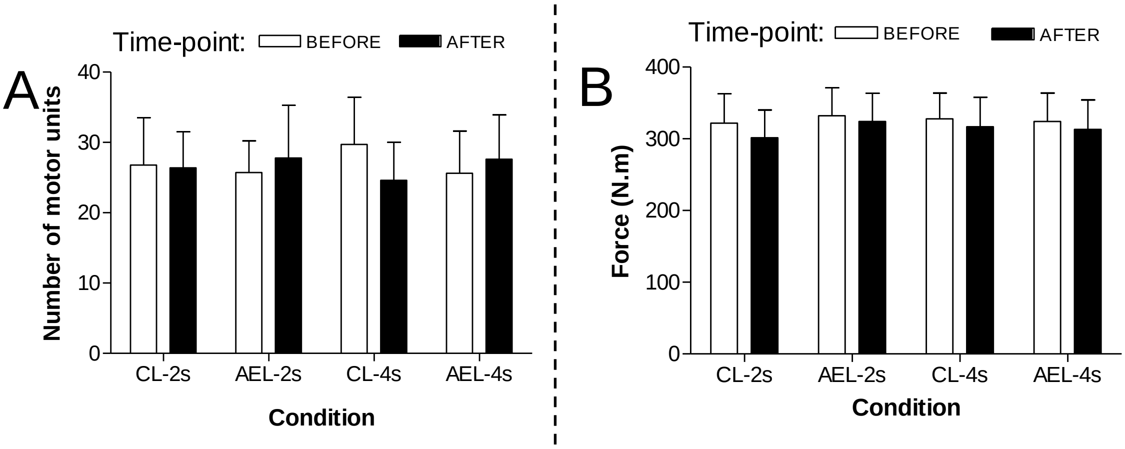


Figure 4.9 Maximum number of detected motor units during isometric trapezoid force efforts (A) and peak force during MVC knee extension efforts (B) in AEL and CL conditions conducted with either a 2 s or 4 s eccentric knee flexion phase.

CL-2s, AEL-2s, CL-4s, and AEL-4s conditions, respectively. After-intervention isometric trapezoid force trace efforts demonstrated 1.6 ± 0.7 errors•s^{-1}, 1.4 ± 0.4 errors•s^{-1}, 1.8 ± 0.6 errors•s^{-1}, and 1.6 ± 0.8 errors•s^{-1} across the duration of the entire trapezoid effort in the CL-2s, AEL-2s, CL-4s, and AEL-4s conditions, respectively.

4.3.4 Absolute reliability, relative reliability, and inter-participant variability of motor unit firing rate data

Table 4.1 demonstrates that the lowest intra-participant coefficient of variation four across motor unit populations were frequently observed in time phase four. Time phase four also displayed the narrowest limits of agreement values for mid-recruited motor units and overall motor unit firing rates. The greatest intraclass correlation coefficient values were displayed in time phases three and four across the motor unit populations (Table 4.2). The lowest inter-participant coefficient of variation was consistently displayed in time phase four across motor unit populations (Table 4.2).

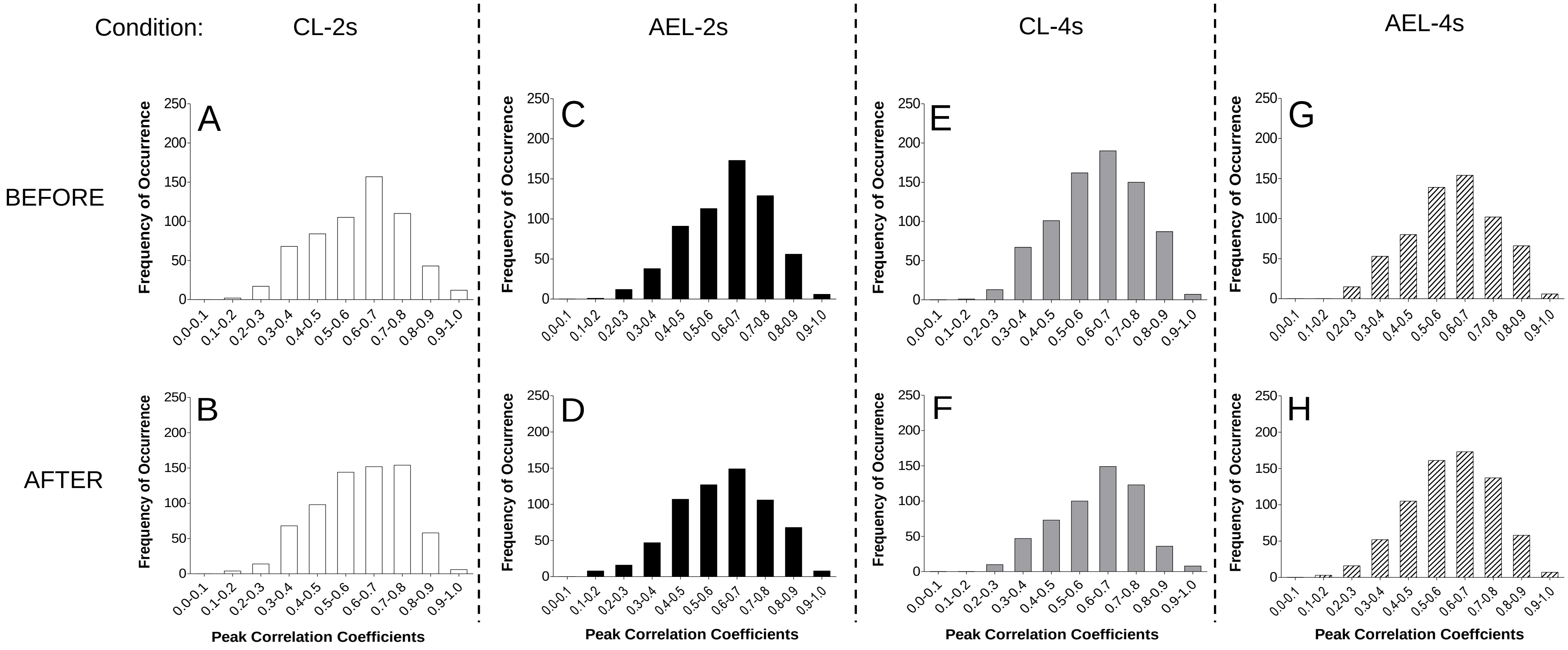


Figure 4.10 Histograms of the maximum cross-correlation coefficients between each pair of motor units that were cross-correlated across all participants before and after AEL and CL conditions completed with either a 2 s or 4 s eccentric knee flexion phase.

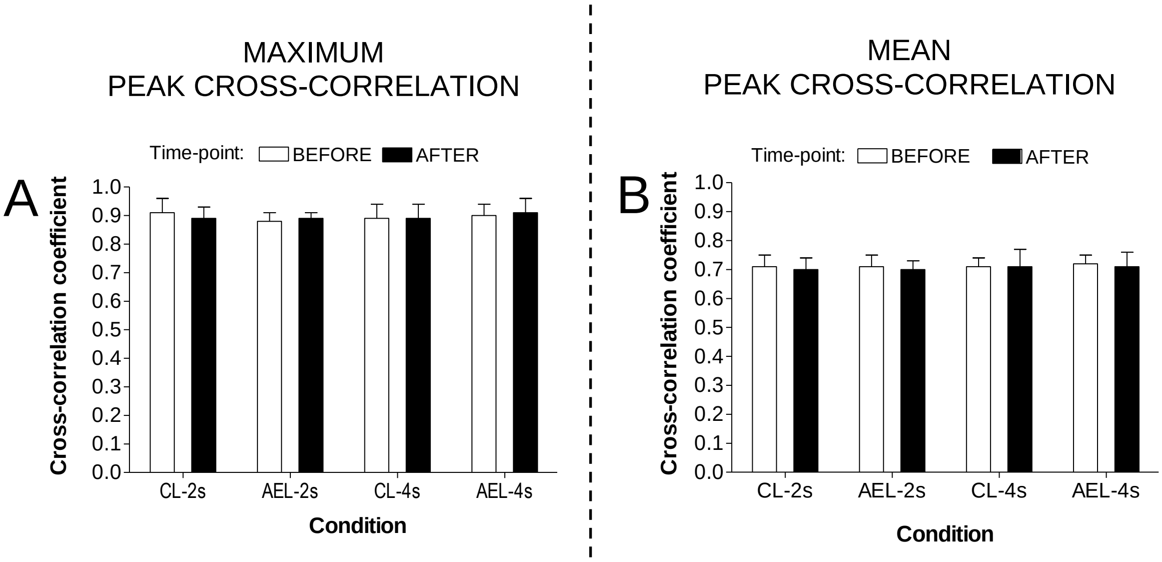


Figure 4.11 Maximum (A) and mean (B) peak cross-correlation coefficients in AEL and CL conditions conducted with either a 2 s or 4 s eccentric knee flexion phase.

4.4 Discussion

4.4.1 Motor unit firing rate, common drive, and force production responses

In this study we demonstrated that the motor unit firing rate of later-recruited motor units was decreased following acute AEL-2s, whilst the motor unit firing rate of earlier-recruited and mid-recruited motor units remained unchanged. Conversely, the firing rate of all motor unit populations was maintained in the AEL-4s condition. In comparison, the firing rates of all motor unit populations remained unchanged following both CL-2s and CL-4s conditions. These findings suggest AEL elicits distinct neuromuscular responses in the later-recruited motor units compared to CL. In contrast, common drive did not differ between conditions with both peak cross-correlation coefficients and frequency histograms remaining unchanged when compared to before-intervention measures. Furthermore, it was shown that the firing frequency of earlier-recruited motor units, mid-recruited motor units, and later-recruited motor units had the greatest absolute reliability towards the end of the plateau phase of the isometric trapezoid force trace efforts.

Table 4.1 Summary of vastus lateralis firing rate absolute reliability measures for earlier-recruited, mid-recruited, and later-recruited motor units. The values in boxes denote the time phase with the greatest reliability for each variable for each motor unit tertile.

		95% Lower limits of agreement			95% Upper limts of agreement			Intra-participant coefficient of variation			Coefficient of variation descriptor
		Mean	±	SD	Mean	±	SD	Mean	±	SD	
Motor unit tertile	Time phase										
Earlier-recruited	1	-13.6	±	4.8	12.7	±	5.0	99.6	±	63.0	Unacceptable
	2	-6.2	±	1.3	6.6	±	3.0	14.3	±	6.2	Acceptable
	3	***-4.3***	***±***	***1.2***	***4.3***	***±***	***1.1***	***7.7***	***±***	***3.9***	Good
	4	-4.7	±	1.0	4.3	±	1.1	7.9	±	4.1	Good
	5	-8.2	±	2.0	7.4	±	2.2	18.5	±	13.4	Acceptable
Mid-recruited	1	-8.3	±	1.9	9.3	±	2.2	149.6	±	63.7	Unacceptable
	2	-6.8	±	1.4	9.5	±	2.6	26.6	±	13.9	Unacceptable
	3	-3.0	±	0.8	6.4	±	1.5	10.0	±	5.4	Good
	4	***-3.2***	***±***	***1.0***	***5.6***	***±***	***1.1***	***8.6***	***±***	***5.2***	Good
	5	-7.6	±	1.7	7.4	±	1.9	35.1	±	30.7	Unacceptable
Later-recruited	1	***-1.9***	***±***	***0.9***	***2.4***	***±***	***0.8***	63.1	±	89.9	Unacceptable
	2	-5.3	±	1.0	8.2	±	2.2	36.4	±	18.7	Unacceptable
	3	-2.6	±	1.4	6.0	±	1.4	12.9	±	9.0	Acceptable
	4	-1.7	±	0.9	3.8	±	0.8	***8.7***	***±***	***5.3***	Good
	5	-3.5	±	0.4	3.7	±	1.0	69.3	±	42.9	Unacceptable
Overall	1	-10.7	±	3.4	10.4	±	3.5	133.2	±	71.8	Unacceptable
	2	-3.7	±	1.0	6.0	±	1.8	14.8	±	6.6	Acceptable
	3	-2.0	±	1.1	5.3	±	1.3	8.2	±	5.2	Good
	4	***-2.5***	***±***	***0.8***	***4.6***	***±***	***0.9***	***7.1***	***±***	***4.7***	Good
	5	-4.1	±	1.4	5.2	±	1.8	15.4	±	9.9	Acceptable

Table 4.2 Summary of vastus lateralis firing rate relative reliability and inter-participant variability measures for earlier-recruited, mid-recruited, and later-recruited motor units. The values in boxes denote the time phase with the greatest reliability for each variable for each motor unit tertile.

		Inter-participant coefficient of variation			Intraclass correlation coefficient of variation			
		Mean	±	SD	Mean	Lower confidence interval	Upper confidence interval	Descriptor
Motor unit tertile	Time phase							
Earlier-recruited	1	99.5	±	11.9	0.60	0.29	0.81	Good
	2	19.7	±	5.3	0.62	0.30	0.82	Good
	3	15.6	±	2.4	***0.74***	***0.49***	***0.88***	Good
	4	***15.3***	***±***	***3.5***	***0.74***	***0.49***	***0.88***	Good
	5	23.4	±	2.5	0.46	0.10	0.73	Poor
Mid-recruited	1	177.5	±	23.4	0.68	0.39	0.85	Good
	2	43.5	±	7.5	0.71	0.44	0.87	Good
	3	21.1	±	4.5	***0.78***	***0.56***	***0.90***	Good
	4	***20.1***	***±***	***4.5***	0.75	0.50	0.89	Good
	5	52.4	±	6.6	0.73	0.48	0.88	Good
Later-recruited	1	240.8	±	37.4	0.39	0.02	0.69	Poor
	2	73.2	±	17.0	0.69	0.40	0.86	Good
	3	29.4	±	5.4	0.79	0.57	0.91	Good
	4	***25.2***	***±***	***5.4***	***0.85***	***0.69***	***0.94***	Excellent
	5	97.4	±	16.7	0.71	0.45	0.87	Good
Overall	1	112.8	±	16.4	0.41	0.04	0.70	Poor
	2	26.1	±	4.5	0.79	0.57	0.91	Good
	3	20.0	±	3.1	***0.83***	***0.65***	***0.93***	Excellent
	4	***18.7***	***±***	***4.0***	0.82	0.63	0.92	Excellent
	5	21.1	±	4.5	0.56	0.23	0.79	Poor

The firing rates of earlier-recruited motor units in the present investigation were, as previously reported, greater than later-recruited motor units (De Luca and Hostage, 2010; De Luca and Erim, 1994; De Luca et al., 1982). The vastus lateralis firing rates reported in the current study are lower than those reported in previous work, in which peak and mean firing rates of 50.0 and 26.4 pulses•s^{-1} were reported (Roos et al., 1999), respectively. Similar average vastus lateralis motor unit firing rates (~20 pulses•s^{-1}) have been reported both before and after resistance training interventions at 50-60% (Stock et al., 2012) and 75% (Pucci et al., 2006) of MVC peak force as those of earlier-recruited motor units in the present study. However, both Pucci et al (Pucci et al., 2006) and Stock et al (Stock et al., 2012) averaged motor unit firing rates rather than using the motor unit population classification system employed in the current study. The reported differences in vastus lateralis firing rate between the current study and previous research is likely due to the different percentages of MVC at which motor unit firing rates were measured and the way firing rates were calculated. Previously, it has been stated that the use of multiple second time periods where constant force is maintained, such as in the current study, provides a better indication of a sustained firing rate than when brief ms time periods are used. This has been attributed to force fluctuations that may occur during brief time periods where motor unit firing rate is calculated (De Luca and Hostage, 2010).

The finding of decreased later-recruited motor unit firing rates may be indicative of; (i) central fatigue (Stock et al., 2012), despite the maintenance of after-intervention MVC force (Behm, 2004); or (ii) an energy preserving intrinsic decrease in motor neuron discharge rate known as “late adaptation” in the AEL-2s condition (Behm, 2004). The reported decrease in motor unit firing rate suggests that AEL performed with a quicker eccentric phase effects neural control and places differential demands on later-recruited motor units compared to CL. The fact that a differential motor unit firing rate response occurred only in the AEL-2s condition suggests the greater force production required in the eccentric phase of this condition as a result of both loading and velocity variables (Farthing and Chilibeck, 2003b) may have caused the altered later-recruited motor unit firing rate response. It is likely therefore, that later-recruited motor units would have been largely responsible for the increased force production under the conditions of the AEL-2s intervention. The acute reduction in motor unit firing rate following the AEL-2s condition is somewhat related with research that has previously shown increases in type IIX muscle fibre cross sectional area beyond changes in the same fibre type with CL during a 6 week training intervention study (Friedmann-Bette et al., 2010). Although, definite conclusions cannot be made regarding the specific type of motor units recruited in the arbitrarily determined earlier-recruited, mid-recruited, and later-recruited populations, motor units of increasing size are recruited with increasing levels of force (Henneman, 1985).

If the decrease in motor unit firing rate in the AEL-2s condition was caused as a result of central fatigue, neuromuscular strategies such as altered motor control may have occurred to allow MVC peak force to be maintained. Previously, it has been demonstrated that altered central excitatory input can increase the activity of other quadriceps muscles to compensate for fatigue of the vastus lateralis (Akima et al., 2002). Alternatively, alterations in antagonist muscle recruitment strategy may have occurred following the intervention (Psek and Cafarelli, 1993). However, motor unit firing rates of the other quadriceps muscles and biceps femoris were not measured during the isometric trapezoid force trace efforts and therefore these suggestions cannot currently be confirmed. The differential firing rate responses in the later-recruited motor units following the AEL-2s intervention could potentially contribute to the superior chronic strength gains that have previously reported with AEL (Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000), especially given the role of higher threshold motor units in maximal force production. However, it remains to be clarified how the acute decrease in later-recruited motor unit firing rate observed in the current study, may influence later-recruited motor units at different stages of a long-term AEL training intervention. Specifically, the acute decrease in later-recruited motor unit firing rate in the current study is in contrast to prior research documenting increases in motor unit firing rate with chronic strength gains following resistance training interventions (Folland and Williams, 2007). The fact that only the AEL-2s condition induced an acute response in firing rate suggests that the velocity of eccentric muscle actions, not just the load employed, influences the acute responses to resistance exercise in a recreational resistance exercising population.

Although the firing rate of later-recruited motor units decreased following the AEL-2s intervention, common drive was unchanged following AEL or CL interventions. The fact that common drive was not affected by any of the interventions despite a decrease in motor unit firing rate suggests that such acute responses can occur independently of common drive adjustments. Consistent with the acute responses in the present study, previous research has reported adaptations in firing rate, but not motor unit synchronisation following a 4 week low force resistance exercise intervention (Griffin et al., 2009). Motor unit synchronisation, like common drive, is quantified by cross-correlation analysis. The lack of alteration of common drive calculated from a large population of motor units following each intervention in the current study indirectly supports existing cross-sectional and training intervention studies, suggesting strength training does not alter common drive (Beck et al., 2011; De Luca et al., 1982). The finding of unaltered common drive following acute resistance exercise involving an overloaded eccentric phase was consistent with other acute research conducting cross-correlational analysis using a greater volume of eccentric exercise to induce muscle damage (Beck et al., 2012), but in contrast to the findings of other studies employing eccentric-focused exercise interventions (Dartnall et al., 2011; Dartnall et al., 2008). The disparity in findings between studies regarding common drive and motor unit synchronisation may be due to differences in the type of electrode employed (high density EMG electrode *vs.* intra-muscular wire electrode) or the type of cross-correlation analyses conducted (Dartnall et al., 2011; Dartnall et al., 2008). There also remains the possibility that acute common drive responses and chronic adaptations may not be related or contribute (Kidgell et al., 2006) to increased strength levels following resistance training interventions (Duchateau et al., 2006). Further research is required to determine if similar motor unit firing rate responses are observed in a multiple-joint AEL model, which has more application for rehabilitative and athletic populations. In addition, research investigating motor unit firing rates responses after repeated training sessions, within an AEL training intervention, are warranted. Determining how acute responses contribute to longer-term neural adaptations would allow for a greater understanding of how chronic concentric and eccentric strength is influenced and also help determine the efficacy of using AEL.

The motor unit firing rate results produced from the current study contradict prior upper-body acute surface EMG findings which did not display differential responses between AEL and CL (Ojasto and Hakkinen, 2009a; Ojasto and Hakkinen, 2009b). Whereas, common drive results from the present investigation are consistent with the lack of neuromuscular responses in comparison to CL reported within the existing acute AEL literature (Ojasto and Hakkinen, 2009a; Ojasto and Hakkinen, 2009b). The discrepancy in findings between the current study and previous research is likely due to the differences in the timing and type of measures quantified. In the previous research surface EMG measures were taken whilst participants performed acute upper-body AEL and represent neuromuscular activation during this task rather than the neural responses that occur afterwards.

4.4.2 Motor unit firing rate absolute, relative and inter-participant reliability

The quality of findings from the current investigation are supported by the “reconstruct and test” analysis (Nawab et al., 2010), which provides quantification of signal decomposition accuracy to ensure users can focus on analysing accurate data, has previously been validated (De Luca and Nawab, 2011; De Luca et al., 2006). However, until now, between-test session reliability of motor unit firing rate data produced from decomposed surface EMG signals does not seem to have been assessed. The finding of greater absolute reliability towards the end of the plateau phase of the isometric trapezoid force trace effort may be due to the stabilisation of motor unit firing rate with time during the sustained isometric contraction (Contessa et al., 2009; Bigland-Ritchie et al., 1983). The large intra-participant coefficient of variation during the recruitment phase of the contraction may be attributed to the greater force fluctuations that are likely to occur during this component of the isometric trapezoid force trace effort. The recruitment phase required fine adjustments in force production to accurately track the force trace curve, as it increased at a set rate of 10% of MVC peak force•s^{-1}. Therefore, during the recruitment phase variance in the ability to precisely track force trace between test session days may have caused additional motor units to be recruited or firing rates to be adjusted within this early part of the isometric trapezoid force trace effort, which may explain the “unacceptable” coefficient of variation values reported for this phase.

4.5 Conclusions

The findings of the current study indicate that single-joint lower-body AEL employing a ~2 s eccentric phase differentially effects motor unit firing rate on an acute basis compared to CL. The lack of alteration of common drive calculated from a large population of motor units following each intervention adds indirect support for existing cross-sectional and training interventions suggesting strength training may not alter common drive. Further research is required to confirm whether or not the same motor unit firing rate response occurs in a multiple-joint lower-body AEL model. In addition, further research should elucidate how acute motor unit firing rate responses change across the course of AEL training programme intervention and how AEL influences both chronic concentric and eccentric strength as a result.

4.6 Contribution of chapter four to the aims of the thesis

The current chapter addressed one of the aims of the thesis by comparing common drive and motor unit firing rate responses after AEL and CL. The results of this chapter are the first to investigate how acute bouts of AEL and CL effect motor unit firing rate and common drive. The results of the current chapter contribute new information to the body of research investigating AEL as existing research has only investigated adaptations and responses of EMG amplitude following AEL training interventions and during acute training bouts, respectively. The findings of the current chapter demonstrated that the firing rates of later-recruited motor units were reduced following an acute bout of AEL completed with a 2 s duration eccentric phase. The acute reduction in motor unit firing rate following lower-body single-joint AEL may provide an indication of the nature of longer-term adaptations that occur with this type of resistance exercise. However, future research incorporating both acute and chronic neuromuscular measurements is required to confirm this. In order to make progress towards attaining the remaining aims of the thesis the approaches employed in Chapter 3 and 4 were applied to a multiple-joint free weight lower-body resistance exercise; the back squat.

CHAPTER 5

ACUTE NEUROMUSCULAR AND KINETIC RESPONSES TO WEIGHT RELEASER HOOK ACCENTUATED ECCENTRIC LOAD BACK SQUATS

Balshaw TG, Chesham RA, Donald N, Hunter AM.

5.1 Introduction

Following the investigation of acute: (i) neuromuscular activation; (ii) kinetic and kinematic; (iii) contractile characteristics; (iv) motor unit firing rate; and (v) common drive responses to lower limb single-joint AEL and CL, the question arose as to whether similar responses would occur in a more complex multiple-joint resistance exercise model. Training interventions comparing AEL and CL have been conducted to assess the efficacy of AEL for enhancing chronic strength adaptations. AEL has been shown to elicit greater strength gains, compared to CL (Norrbrand et al., 2008; Friedmann et al., 2004; Brandenburg and Docherty, 2002; Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000; Kaminski et al., 1998). However, other AEL training intervention studies have demonstrated strength adaptations to equate those seem with CL (Friedmann-Bette et al., 2010; Yarrow et al., 2008; Barstow et al., 2003; Godard et al., 1998; Ben-Sira et al., 1995; Nichols et al., 1995). The ambiguous findings in the existing AEL training intervention research may be due, in part, to the differences in the way that AEL has been implemented. Flywheel devices (Norrbrand et al., 2008), resistance machine (Friedmann et al., 2004; Barstow et al., 2003; Hortobagyi et al., 2001a; Ben-Sira et al., 1995), and free weight variations (Yarrow et al., 2008; Brandenburg and Docherty, 2002) each have different configurations affecting the amount of load that can be applied during AEL, how quickly transitions between eccentric and concentric phases of the particular exercise can be made, and the extent of effort required to stabilise the body in order to maintain exercise posture in response to gravity, ground reaction forces, and momentum. Furthermore, many of these AEL devices are not portable, financially feasible, or commercially available.

Free weight resistance exercise is frequently selected rather than over resistance machines within both athletic and rehabilitative populations. Lower-body resistance exercises, such as the free weight back squat are considered to result in strength gains in anterior (knee extensor) and posterior (hip extensor) musculature that are more transferable to real-world athletic events and mobility compared to machine-based resistance exercise, due to the greater neuromuscular activation and intermuscular coordination involved (Young, 2006). However, to date, only a single AEL free weight squat-based training programme intervention has been conducted

(Yarrow et al., 2008). This study utilised free weight resistance exercise combined with a commercially unavailable selectorised electric motor resistance machine to implement AEL (Yarrow et al., 2008). Weight releaser hooks (Doan et al., 2002) that can be applied during the free weight barbell back squat represent a portable, commercially available, and financially feasible way to implement AEL in applied training settings (GETSTRENGTH, 2013). The use of weight releaser hooks during the back squat resistance exercise presents a unique set of demands to the individual performing the exercise given the additional eccentric phase load, the distribution of this load, and the unassisted removal of the weighted hooks prior to the concentric phase of each repetition. However, despite suggestions that acutely overloading the eccentric phase may cause additional α motor neurons to be recruited during the subsequent concentric phase of an AEL exercise (Doan et al., 2002) no lower-body study has investigated neuromuscular activation during a key lower-body free weight exercise such as the free weight back squat. Acute concentric kinetic responses to ballistic lower-body AEL exercises have previously been investigated (Moore et al., 2007; Sheppard et al., 2007) and recently a study was completed comparing knee extensor neuromuscular and kinetic responses in an AEL flywheel squat model. However, these acute lower-body studies have either not measured neuromuscular activation (Moore et al., 2007; Sheppard et al., 2007) or use resistance exercise models that are dissimilar to traditional resistance training equipment and are predominantly used during space flight (Norrbrand et al., 2011).

Determining the acute kinetic and neuromuscular activation responses to AEL barbell squats conducted with weight releaser hooks would inform the prescription or refinement of resistance training programmes for individuals within athletic and rehabilitative training settings. The results produced from such an investigation would help exercise professionals to decide whether or not to employ AEL with their athletes or patients, during which training phase this back squat variant could be implemented, and how AEL may acutely effect neuromuscular control compared to CL squats.

Specifically, this approach would assess how the unique demands of weight releaser hook AEL back squats influence: (i) the magnitude of kinetic outputs produced across a range of concentric phase loads; (ii) the extent and rate of force production during the eccentric phase of the exercise; (iv) the amount of neuromuscular activation from key knee and hip extensor musculature; and (iv) the neuromuscular activation contributions from and interactions between lower-body agonist muscles. Such an investigation may be particularly informative for practitioners given the contrasting results reported in the AEL *vs.* CL training intervention literature. Therefore, the purposes of the current study were threefold: firstly, to compare acute kinetic outputs between AEL and CL squats; secondly, to investigate how the extent of acute neuromuscular activation is effected when back squats are completed with and without weight releaser hooks; and thirdly, to examine how acute activation contributions from and interaction between anterior and posterior lower-body musculature are effected during weight releaser AEL compared to CL squats. In Chapter 2 normalisation methods during the free weight back squat were assessed. Submaximal dynamic surface EMG normalisation methods were identified as having the greatest absolute reliability between-test days. Therefore, submaximal normalisation methods were selected to allow comparisons between neuromuscular activation during AEL and CL free weight back squats within the current chapter.

5.2 Methods

5.2.1 Participants

Ten strength-trained males (aged: 28.5 ± 6.2 years, body mass: 83.7 ± 10.1 kg, height: 1.75 ± 0.08 m, sum of seven skin folds: 65.4 ± 16.9 mm, mean ± SD), experienced with the free weight back squat and repetition maximum testing (relative 3RM back squat strength: 1.7 ± 0.2 times body mass, absolute 3RM back squat back squat barbell load: 141.5 ± 18.3 kg) took part in the study. Ethical approval was obtained from the University of Stirling Research Ethics Committee. All participants provided written informed consent prior to testing. The study was conducted in accordance with the principles outlined in the Declaration of Helsinki (2008).

5.2.2 Procedures

3RM back squat

Baseline 3RM back squat testing was performed to allow load prescription during experimental condition test sessions. Maximum strength testing commenced with incremental intensity warm-up sets, in order to prepare participants for up to five attempts at establishing 3RM to the nearest 2.5 kg. 3RM rather than 1RM testing was used as subsequent experimental sessions involved multiple sets with 3 repetitions prescribed. Multiple repetition maximum tests have previously been demonstrated to be reliable with individuals familiar with this type of testing (Taylor and Fletcher, 2012). Olympic standard barbell and weight plates were used during all test sessions (Eleiko Sport, Halmstad, Sweden). Recovery between each of the warm-up sets and 3RM attempts was set at 3-mins (Harman, 2008). Participant squat stance width was marked and measured prior to the warm-up and was used in all subsequent sessions. During all back squat repetitions completed in the 3RM and the subsequent experimental test day sessions exercise posture was monitored to ensure hip and knee joint angles remained constant between conditions. Knee joint angles were monitored using a two-dimensional electrogoniometer (TSD130B, Biopac Systems Inc, California, USA) and integrated hardware (Biopac MP100, Biopac Systems Inc, California, USA) and software (AcqKnowledge®, Version 3.9, Biopac Systems Inc, California, USA). The upper unit of the electrogoniometer was attached to the thigh and the lower unit was secured to the shank of the participant’s dominant leg using micropore tape. Measures produced from the goniometer were used to ensure sufficient knee joint range of movement (Caterisano et al., 2002). No differences in knee joint angle were detected at the lowest part of the back squat between conditions ($p= 0.187$, $f= 2.04$; mean across sets: AEL: 68.7 ± 1.3°, CL: 65.9 ± 0.4°, mean ± SD, 180° equalling full knee extension). Hip joint angles were controlled by visually monitoring the forward lean of the torso to ensure hip joint flexion was not excessive, as previously described (Caterisano et al., 2002).

Application of additional eccentric load via weight releaser hooks

The sum of the barbell load for the heaviest successful 3RM attempt and 88.6% of body mass were used to establish 3RM back squat system mass (Brandon et al., 2011), as decribed in Chapter 2 (section 2.2.2). The loads applied to the barbell and weight releaser hooks during back squat repetitions were prescribed in order to equate percentages of 3RM system mass. The eccentric phase load during AEL back squat repetitions was produced through the combination of: (i) the load applied to the barbell; and (ii) the additional load attached via custom-built adjustable weight releaser hooks (Doan et al., 2002), at each end of the barbell (Figure 5.1). Assistants responded to verbal signals from the participant to apply the hooks at each end of the barbell, ensuring simultaneous application of the hooks and balance of the load on the participant's shoulders, before the start of each repetition. At the bottom position of the back squat, the load applied by each weight releaser hook was automatically removed from the barbell by the contact of the bottom of each hook with custom-built adjustable platforms positioned at either side of the squat rack.

Kinetic data capture

Kinetic data during all experimental back squat repetitions completed in the study were recorded using an integrated force platform (400 Series force platform, Fitness Technology, Adelaide, Australia), linear transducer (Celesco PT5A, Chatsworth, Califronia, USA), and software (Ballistic Measurement System, Version 2011.0.3, Fitness Technology, Adelaide, Australia) system. The force platform and transducer were calibrated against known forces and distances

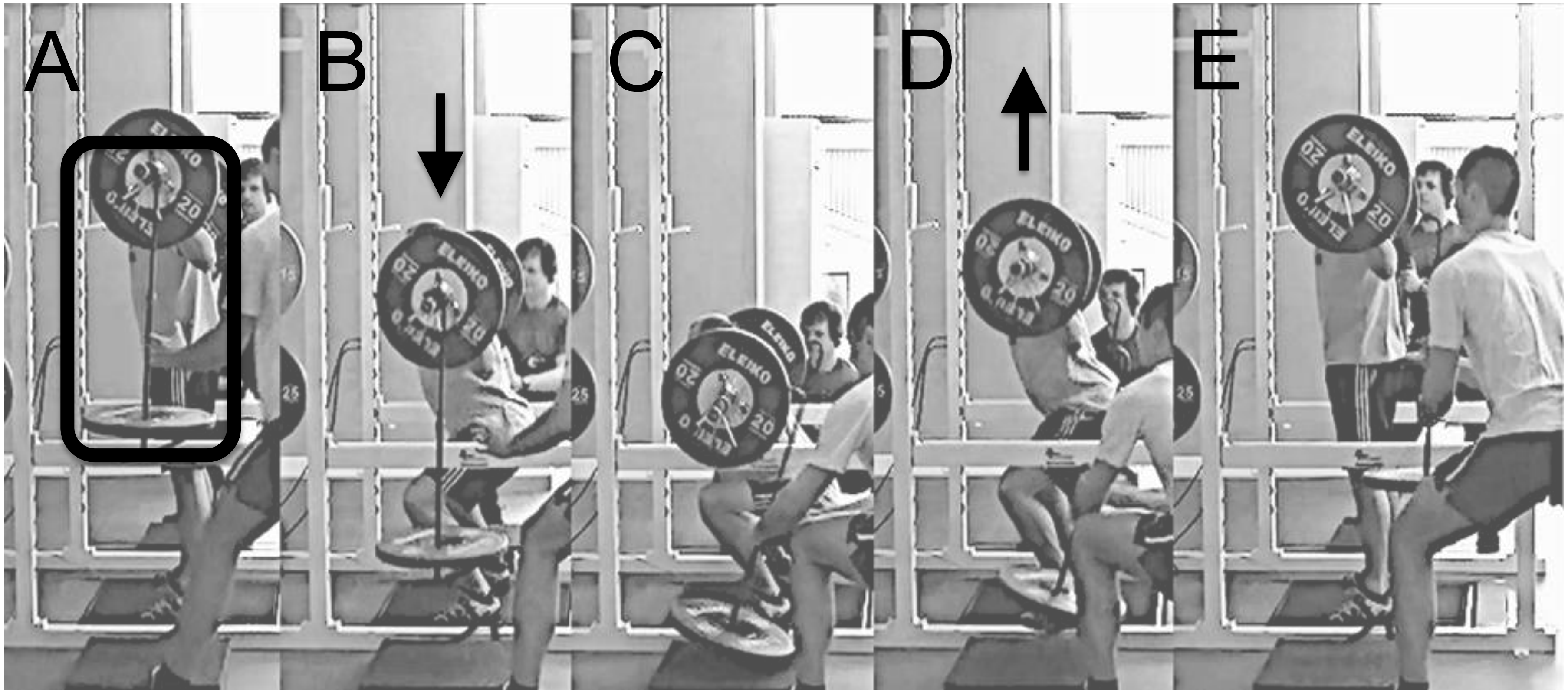


Figure 5.1 Application and release of the AEL weight releaser hooks. (A) Participant free standing at start of squat repetition following synchronised application of additional eccentric load (denoted by black line box) via releaser hooks applied by assistants at either end of the barbell. (B) Descent of barbell during the eccentric phase of the back squat. (D) Bottom position of the back squat where weight releaser hooks are removed from the barbell as the base of the hooks contact the customised height releaser platform (D) Ascent of the barbell during the concentric phase of the back squat following removal of weight releaser hooks. (E) End of the concentric phase, assistants ready to apply weight releasers for the subsequent repetition.

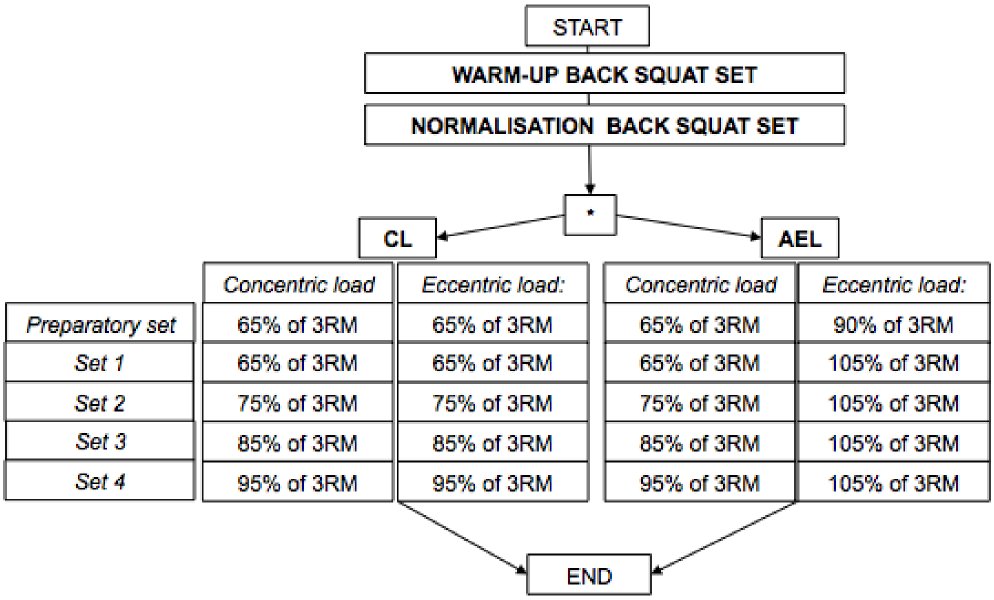
(Sheppard et al., 2008b). Participants performed all back squat repetitions in each experimental condition whilst standing on the force platform and having the transducer secured to their barbell. The transducer was mounted overhead to the squat rack frame that back squat repetitions were performed within. Kinetic data were sampled at a frequency of 200 Hz (Hori et al., 2009; Hori et al., 2008; Hori et al., 2007). All force platform and linear transducer data were filtered with a cut-off frequency of 10 Hz using a forth order Butterworth digital filter.

5.2.3 Experimental protocol

Participants reported for four separate test sessions over a 4 week period. Participants avoided exhaustive exercise in the 24 h prior to each test session and replicated 48 h food and fluid intake diaries recorded prior to the first session before all remaining test sessions. Back squat 3RM was established in the first session. The second lab visit was used to the familiarise participants with performing AEL back squats. During the familiarisation session participants completed sets of three AEL back squat repetitions using a 65% of 3RM concentric phase load and additional load applied via weight releaser hooks during the eccentric phase to equate loads ranging from 90% of 3RM up to the 105% of 3RM. Once participants were accustomed to performing AEL squats with the 105% of 3RM eccentric phase load AEL sets with 75-85% of 3RM in the concentric phase were performed.

The third laboratory visit involved the randomised completion of either AEL or CL squats (Figure 5.2). In the final laboratory session the remaining experimental condition was completed. Experimental condition test sessions were separated by 5 d. Before experimental condition back squat sets commenced two back squat warm-up sets were completed. Each warm-up set consisted of five repetitions, performed at 70% and 80% of 3RM system mass, respectively. During warm-up sets both the eccentric and concentric phases were completed in time with audible tones produced by a custom-built metronome. Inter-tone time (eccentric: 1.6 ± 0.4 s; concentric: 2.4 ± 0.5 s) was determined from 3RM barbell displacement data recorded via the same integrated force platform and transducer system, used to collect kinetic data during all back squat repetitions, in order to equate the velocity during the heaviest successful 3RM attempt.

Following warm-up sets, participants performed a further preparatory set consisting of three repetitions. The CL condition preparatory set involved a 65% of 3RM system mass load for both the eccentric and concentric phases. The preparatory set in the AEL condition consisted of a 90% of 3RM system mass eccentric phase load and a 65% of 3RM system mass load during the directly subsequent concentric phase. From the preparatory set onwards, participants completed the eccentric phase of each repetition in time with the audible tones from the custom-built metronome, transitioned as quickly as possible between phases, and performed the subsequent concentric phase as explosively as possible. The audible tones from the custom-built metronome were effective in matching eccentric phase duration between sets as no differences between conditions were observed (p= 0.269; f= 1.39; mean ± SD across sets: AEL: 1.5 ± 0.5 s, CL: 1.3 ± 0.3 s). The four back squat sets in each condition (AEL or CL), following the preparatory set, involved concentric phase loads of 65% of 3RM system mass load (set 1), 75% of 3RM system mass load (set 2), 85% of 3RM system mass load (set 3), and 95% of 3RM system mass load (set 4). The eccentric phase loads in the CL condition were the same as the concentric phase load in each set, whereas the eccentric phase load in the AEL condition was held constant at 105% of 3RM across sets. A 105% of 3RM eccentric overload was selected based on pilot work completed with a strength-trained population suggesting this load was the heaviest load that could be applied for multiple sets and also allowed participants to maintain correct back squat range of movement and posture. Each experimental set, regardless of condition, consisted of three repetitions. As the purpose of the study was to compare kinetic and neuromuscular responses to AEL and CL rather than induce



	CL		AEL	
	Concentric load	*Eccentric load:*	*Concentric load*	*Eccentric load:*
Preparatory set	65% of 3RM	65% of 3RM	65% of 3RM	90% of 3RM
Set 1	65% of 3RM	65% of 3RM	65% of 3RM	105% of 3RM
Set 2	75% of 3RM	75% of 3RM	75% of 3RM	105% of 3RM
Set 3	85% of 3RM	85% of 3RM	85% of 3RM	105% of 3RM
Set 4	95% of 3RM	95% of 3RM	95% of 3RM	105% of 3RM

Figure 5.2 Experimental condition protocol. * denotes randomisation of experimental conditions.

muscle damage, a set and repetition configuration designed to elicit high force and power outputs whilst still performing multiple repetitions was selected, rather than a high volume set and repetition protocol. Training volume (mass x repetitions x number of sets) was calculated for concentric and eccentric phases of the back squat in each condition (Kramer et al., 1997). Concentric phase training volume was 1,172.3 ± 159.8 kg in both conditions. Eccentric phase training volume was 1,815.0 ± 229.9 kg and 1,172.3 ± 159.8 kg and in the AEL and CL conditions, respectively. The eccentric phase training volume was 55.1 ± 3.5% greater in the AEL compared to the CL condition.

5.2.4 Kinetic data analysis

Back squat concentric phase peak force and peak power values produced during each repetition in both conditions were extracted from kinetic data capture files. The mean of concentric kinetic variables across repetitions within each set was used for analysis. The extraction of concentric phase kinetic data was achieved by analysing force and power within each period where the barbell was moved from its lowest height to its greatest height, as determined from linear transducer displacement data. Concentric phase back squat peak force and peak power data displayed mean intra-participant coefficients of variation ranging from 1.3-2.4% and 2.6-5.7%, respectively, when this absolute reliability measure was calculated for each set in both conditions. As the eccentric back squat phase duration was controlled via audible tones from a custom-built metronome the magnitude and rate of loading during this phase was quantified from force data by analysing eccentric mean force and rate of force development (Ebben et al., 2010). Eccentric rate of force development was calculated for each repetition by subtracting the force value 250 ms prior to peak force from peak eccentric force and dividing by the time elapsed between these two values (250 ms). Mean eccentric mean force and rate of force development values were determined across repetitions within each set in each experimental condition and were used for analysis. The extraction of eccentric phase kinetic data was accomplished by analysing force within each repetition where the barbell was moved from its highest height to its lowest height, as determined from linear transducer displacement data. Eccentric phase back squat mean force and rate of force development data displayed mean intra-participant coefficients of variation ranging from 0.2-1.2% and 11.8-18.2%, respectively, when this absolute reliability measure was calculated for each set in both conditions.

5.2.5 Electromyography

Electromyography data collection

Vastus lateralis, vastus medialis, biceps femoris, and gluteus maximus electromyography was recorded (Biopac MP100, Biopac Systems Inc, California, USA) from each participant’s dominant leg during all warm-up, preparatory, and experimental back squat sets in each experimental condition. Skin preparation was conducted as described in Chapter 2 (section 2.2.4). A bipolar electrode configuration (VERMED A10009-100 ECG diagnostic electrodes, Vermont, USA) was applied to each muscle in accordance with the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles guidelines (Hermens et al., 2000). Specifically, the bipolar electrode configuration with a 2 cm inter electrode distance was applied at the following locations: vastus lateralis; as described in Chapter 2 (section 2.2.4), vastus medialis; 80% on the line between the anterior spina iliaca superior and the joint space in front of the anterior border of the medial ligament, biceps femoris; as described in Chapter 2 (section 2.2.4), gluteus maximus; 50% on the line between the sacral vertebrae and the greater trochanter (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles, 2013). A reference electrode was attached to the patella of the participant's dominant leg. Following the first experimental test day, participants remarked the electrode sites with indelible ink to ensure placement was the same for their second test day. Electromyography data were sampled at a rate of 1500 Hz and anti-aliased with a 500 Hz low pass filter. A 10 Hz high pass filter was also applied. The Biopac MP100 system had an input impedance and common mode rejection ratio of 2MΩ and >110 dB, respectively.

Electromyography data processing

Electromyography amplitude was established by root mean square processing the entire signal, with average root mean square calculated for a moving window 100 ms time period across the entire waveform for each muscle. This processing method was applied to electromyography data collected from the 80% of 3RM warm-up set conducted on each test day and all experimental back squat sets in each condition. Root mean square processing was used to analyse electromyography based on previous recommendations for research investigating neuromuscular activation levels (Hägg et al., 2004). Electromyography processing was completed using the software used to operate the electromyography system (AcqKnowledge® 3.9.1, Biopac Systems Inc, California, USA) according to the system manufacturer's guidelines (Acqknowledge® software guide, 2008).

Electromyography data extraction

The mean root mean square processed electromyography amplitude from the concentric and eccentric phase of 80% of 3RM warm-up and experimental condition set repetitions was extracted. The eccentric and concentric phase electromyography during experimental condition back squats was determined from joint angle data collected from the two-dimensional electrogoniometer that was attached to the participant's dominant leg during all test sessions. Electromyography within the period from the greatest to the smallest knee joint angle in each repetition was classified as eccentric phase data given that full knee extension was classified as 180°. Whereas, electromyography data within the period from the smallest to the greatest knee joint angle in each repetition was classified as the concentric data. Mean root mean square electromyography data from each experimental condition set repetition was normalised to the root mean square electromyography from the corresponding muscle action phase of the 80% of 3RM system mass load warm-up set, conducted at the start of the same test session. Root mean square electromyography from the experimental conditions was normalised to the 80% of 3RM warm-up set to assess differences between conditions. This normalisation method had demonstrated the greatest absolute reliability between-test days compared to other methods in Chapter 2 of this thesis (section 2.3.2).

5.2.6 Statistical analyses

Absolute reliability of kinetic variables measured during each experimental condition was quantified by calculating the intra-participant coefficient of variation from repetitions within each experimental condition set ((mean ÷ SD) x 100). The standard deviation of the two repetitions that produced the greatest kinetic output within each set was divided by the mean of these two repetitions and multiplied by one hundred to produce the intra-participant coefficient of variation. The mean coefficient of variation for each kinetic variable was taken across both experimental conditions for each set.

Minitab 16 statistical software (Minitab Ltd., Coventry, UK) was used to conduct all statistical analysis. Normality of kinetic and electromyographical variables was confirmed following the assessment of Q-Q plots and constant variance. A set (set 1 *vs.* set 2 *vs.* set 3 *vs.* set 4) x condition (AEL *vs.* CL) repeated measures analysis of variance was conducted on kinetic data. Set (set 1 *vs.* set 2 *vs.* set 3 *vs.* set 4) x condition (AEL *vs.* CL) and muscle (vastus lateralis *vs.* vastus medialis *vs.* biceps femoris *vs.* gluteus maximus) x condition (AEL *vs.* CL) repeated measures analysis of variance were used to assess neuromuscular activation and neuromuscular contributions from knee and hip extensor muscles between conditions, respectively. The approach of comparing neuromuscular activation contributions between knee and hip extensor muscles was adopted from previous electromyographical analysis research (Ayotte et al., 2007). Tukey *post-hoc* analysis was used to determine where differences between conditions, sets, and muscles occurred. The *post-hoc* test also allowed interaction effects to be assessed. A significance level of p< 0.05 was selected to determine statistical differences. All values reported are means ± SD.

5.3 Results

5.3.1 Kinetic variable differences during the concentric and eccentric phases of back squats

No condition (p= 0.974, f= 0.00) or condition-load interaction (p= 0.391, f= 1.04) effects were reported for concentric phase peak force (Figure 5.3 A). Condition (p= 0.273, f= 1.36) and condition-load interaction (p= 0.383, f= 1.06) effects were also absent for peak power (Figure 5.3 B). Load effects were observed with increases in concentric peak force (p< 0.001, f= 96.93) and decreases in concentric peak power (p= 0.016, f= 4.08) occurring with load increments between 65 to 95% of 3RM (Figure 5.3 A and B). Condition (p< 0.001, f= 271.88), set (p< 0.001, f= 910.94), and condition-set interaction (p< 0.001, f= 168.63) effects occurred for eccentric phase mean force.

Eccentric phase mean force was 30.4 ± 3.3%, 22.2 ± 2.0%, 14.4 ± 1.5%, and 6.9 ± 0.9% greater in the AEL compared to the CL condition in sets one, two, three, and four, respectively (Figure 5.3 C). No condition (p= 0.419, f= 0.72), set (p= 0.695, f= 0.49), or condition-set interaction (p= 0.473, f= 0.86) effects occurred for eccentric rate of force development (Figure 5.3 D).

5.3.2 Differences in neuromuscular activation between conditions

No differences between AEL and CL conditions were detected for concentric neuromuscular activation of the vastus lateralis (p= 0.560, f= 0.37), biceps femoris (p= 0.126, f= 2.84), vastus medialis (p= 0.887, f= 0.02), or gluteus maximus (p= 0.090, f= 3.61; Table 5.1). Increased concentric phase neuromuscular activation did occur across loads in the biceps femoris (p< 0.001, f= 22.60), vastus medialis (p= 0.031, f= 3.45), and gluteus maximus (p< 0.01, f= 10.09). No load effect (p= 0.560, f= 0.37) was observed for concentric vastus lateralis electromyography but condition-load interaction effects (p= 0.022, f= 3.76) did occur for this muscle. No condition-load interaction effects were demonstrated for concentric vastus medialis (p= 0.462, f= 0.88), biceps femoris (p= 0.820, f= 0.31), or gluteus maximus (p= 0.154, f= 1.90) EMG.

As a product of the greater eccentric phase load in the AEL condition eccentric neuromuscular activation was greater for the vastus lateralis (p= 0.004, f= 14.48), biceps femoris (p= 0.026, f= 7.09), vastus medialis (p= 0.002, f= 19.46), and gluteus maximus (p= 0.011, f= 10.30) in the AEL than the CL condition. Condition-set interactions were observed for eccentric vastus lateralis (p< 0.001, f= 15.58), biceps femoris (p= 0.003, f= 6.10), vastus medialis (p< 0.001, f= 10.77), and gluteus maximus (p= 0.001, f= 7.98) EMG. *Post-hoc* analysis following the detection of a condition-set

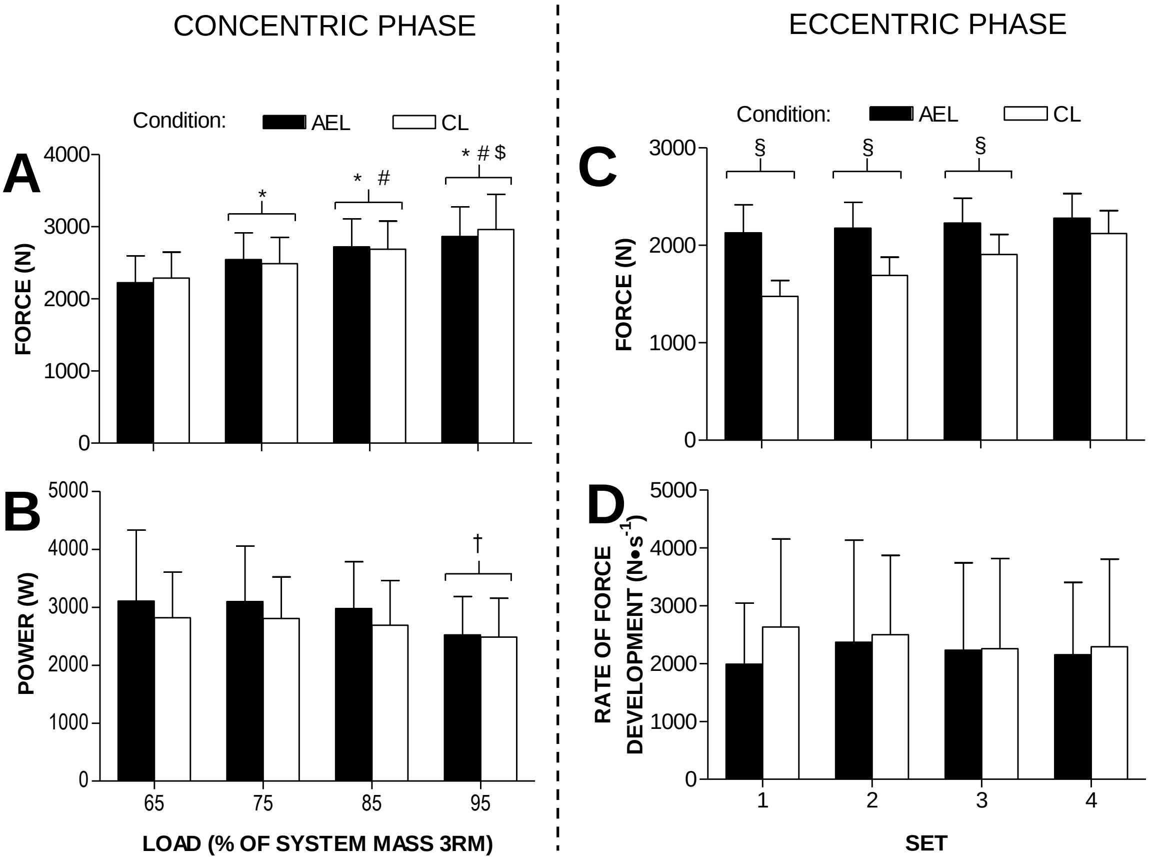


Figure 5.3 Concentric peak force (A), concentric peak power (B), eccentric mean force (C), and eccentric rate of force development (D) in AEL and CL back squat conditions. * denotes greater force ($p < 0.05$) produced than at 65% of three repetition maximum (3RM). # denotes greater force ($p < 0.05$) produced than at 75% of 3RM. $ denotes greater force ($p < 0.05$) produced than at 85% of 3RM. † denotes smaller power output ($p < 0.05$) than at 75%, 85%, or 95% of 3RM. § denotes greater force ($p < 0.05$) produced in AEL than CL condition in corresponding set.

interaction effect demonstrated that eccentric vastus lateralis and vastus medialis EMG remained elevated in the AEL compared to the CL condition in all but the final set (Table 5.1). The *post-hoc* analysis also demonstrated that eccentric biceps femoris and gluteus maximus EMG were only greater in the AEL condition for the first two sets (Table 5.1). Set effects were also demonstrated for eccentric vastus lateralis ($p < 0.001$, f= 27.53), vastus medialis ($p < 0.001$, f= 64.76), biceps femoris ($p = 0.001$, f= 7.14), and gluteus maximus ($p < 0.001$, f= 10.44) EMG.

5.3.3 Differences in neuromuscular activation between muscles within each condition

No differences between AEL and CL conditions were detected for concentric neuromuscular EMG at 65% (p= 0.416, f= 0.73), 85% (p= 0.436, f= 0.66), or 95% (p= 0.904, f= 0.02) of 3RM. A condition effect (p= 0.044, f= 5.50) was found at 75% of 3RM for concentric EMG. Muscle effects were observed for concentric EMG at 85% (p= 0.040, f= 3.18) and 95% (p= 0.001, f= 7.39) of 3RM, but not at 65% (p= 0.684, f= 0.50) or 75% (p= 0.428, f= 0.96) of 3RM. Condition-muscle interaction effects only occurred at 75% of 3RM (p= 0.003, f= 5.84), not at 65% (p= 0.196, f= 1.67), 85% (p= 0.195, f= 1.68), or 95% of 3RM (p= 0.107, f= 2.24) (Figure 5.4). In the AEL condition at 75% of 3RM concentric biceps femoris EMG was 20.8 ± 27.5% greater than that of the vastus lateralis (Figure 5.4 C).

Condition effects indicating greater eccentric EMG in the AEL condition occurred in set 1 (p< 0.001, f= 46.60), set 2 (p< 0.001, f= 50.63), and set 3 (p= 0.006, f= 12.86), but not in set 4 (p= 0.246, f= 1.54) of 3RM. Muscle effects were observed in set 2 (p= 0.021, f= 3.80), set 3 (p= 0.006, f= 5.09), and set 4 (p< 0.001, 10.04), but not in set 1 for eccentric EMG. Condition-muscle interaction effects were displayed for eccentric EMG in set 1 (p= 0.15, f= 4.20) and set 2 (p< 0.001, f= 9.64), but not in set 3 (p= 0.668, f= 0.53) or set 4 (p= 0.978, f= 0.06). Eccentric phase gluteus maximus EMG during the second AEL set was 15.1 ± 15.8%, 17.4 ± 21.4%, and 30.3 ± 19.9% greater than that of the vastus lateralis, vastus medialis, and biceps femoris, respectively (Figure 5.4 D).

5.4 Discussion

Numerous AEL training programme intervention studies have previously been conducted (Friedmann-Bette et al., 2010; Norrbrand et al., 2008; Yarrow et al., 2008; Brandenburg and Docherty, 2002; Hortobagyi et al., 2001a; Nichols et al., 1995).

Table 5.1 Concentric and eccentric neuromuscular activation of the knee and hip extensor muscles during weight releaser hook AEL and CL free weight back squats.

Muscle action phase	Condition	Load or Set	Vastus lateralis			Vastus medialis			Bicep femoris			Gluteus maximus		
			Mean	±	SD	Mean	±	SD	Mean	±	SD	Mean	±	SD
Concentric	AEL	65% of 3RM	126.1	±	34.4	129.3	±	32.4	128.9	±	34.7	127.8	±	39.3
	CL		125.7	±	23.5	127.0	±	35.7	117.2	±	44.2	123.4	±	37.7
	AEL	75% of 3RM	128.4	±	20.4	137.4	±	27.0	149.0	±	32.2	143.7	±	35.0
	CL		128.1	±	17.8	135.4	±	27.6	127.9	±	30.7	125.7	±	37.6
	AEL	85% of 3RM	129.5	±	13.4	143.1	±	28.9	165.1	±	57.6	143.6	±	29.1
	CL		137.2	±	21.8	138.0	±	23.2	150.6	±	43.7	139.1	±	33.4
	AEL	95% of 3RM	127.6	±	16.5	150.7	±	29.7	185.9	±	39.7	157.1	±	29.5
	CL		141.5	±	19.4	139.1	±	30.1	173.5	±	43.7	159.1	±	34.1
Eccentric	AEL	Set 1	120.1	±	13.9*	122.2	±	13.7*	116.6	±	21.9*	139.4	±	42.4*
	CL		86.5	±	14.3	86.5	±	9.1	93.0	±	15.4	75.3	±	13.7
	AEL	Set 2	128.3	±	13.4*	130.7	±	20.6*	111.8	±	11.7*	145.4	±	19.4*
	CL		99.7	±	12.4	102.9	±	11.0	95.6	±	14.8	93.3	±	9.2
	AEL	Set 3	128.1	±	11.8*	135.3	±	17.8*	110.3	±	9.2	137.7	±	36.0
	CL		111.8	±	16.5	115.2	±	12.8	101.4	±	18.1	116.2	±	24.4
	AEL	Set 4	131.3	±	19.1	140.2	±	17.0	115.4	±	9.0	145.0	±	40.3
	CL		127.8	±	16.4	133.2	±	14.0	108.0	±	19.5	136.9	±	22.1

* denotes greater neuromuscular activation at $p < 0.05$ level compared to the same set in the CL condition.

However, equivocal strength adaptation findings in the AEL training intervention research, the range of different techniques and equipment used to implement AEL, and the inconsistency in both strength and physiological measures performed across AEL studies leave question marks over the efficacy of AEL. Consequently, these issues make it difficult for exercise professionals to draw conclusions on what effect employing AEL in a free weight barbell back squat model may have on chronic strength adaptations following AEL or the acute neuromuscular control and kinetic parameters their athletes or patients are exposed to during such training. The purpose of the current study was to investigate kinetic and neuromuscular responses during weight releaser hook AEL back squats in order to provide practitioners with information regarding how implementing lower-body AEL may influence acute training programme parameters.

Evidence exists both for (McBride et al., 2002; Wilson et al., 1993) and against (Young, 2006; Toji and Kaneko, 2004; Harris et al., 2000) the use of training loads that produce optimal acute kinetic outputs within training interventions. Regardless of whether or not training load is maintained throughout an intervention it is important to determine how exercise variations influence kinetic outputs in order to establish safe, effective, and exercise-specific training recommendations for athletes and exercise-intolerant populations. The results of the current study indicated that weight releaser hook AEL back squats equate concentric phase peak power and force output during CL squats. The concentric phase kinetic findings from the current study were in contrast to previous research investigating acute kinetic outputs during heavy upper-body free weight AEL (Doan et al., 2002) and ballistic lower-body AEL models completed without an externally loaded concentric phase (Sheppard et al., 2007). However, the finidngs of the current investigation were consistent with an AEL loaded lower-body ballistic resistance exercise model (Moore et al., 2007). The fact that acute concentric kinetic enhancements in the AEL condition were not observed in the current

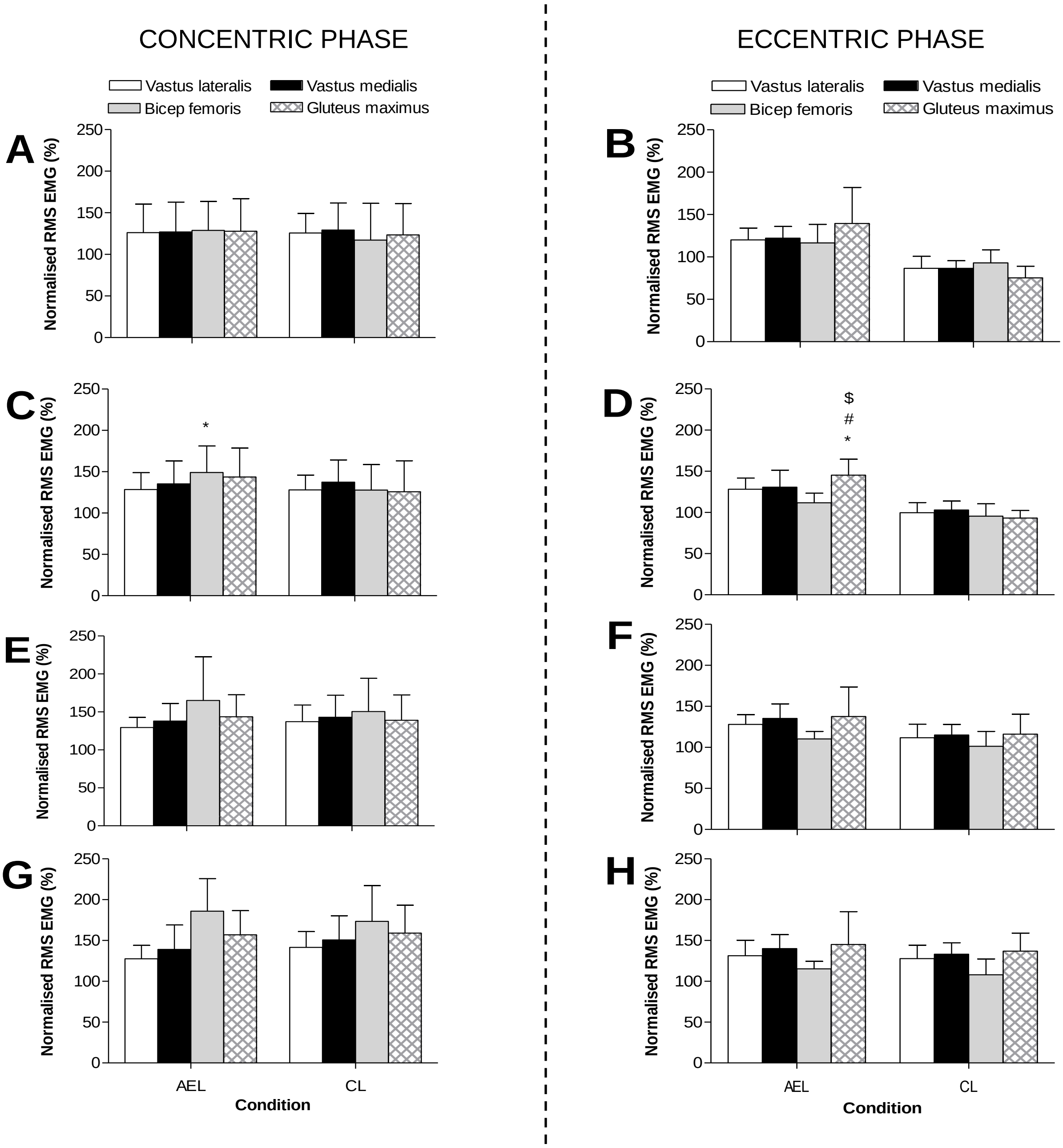


Figure 5.4 Concentric and eccentric EMG of the knee and hip extensor muscles during weight releaser hook AEL back squats and CL back squats at 65% of 3RM load (A and B), 75% of 3RM (C and D), 85% of 3RM (E and F), and 95% of 3RM (G and H). Note that in the eccentric phase in the AEL condition eccentric phase load was held constant at 105% of 3RM across sets. * denotes greater neuromuscular activation compared to vastus lateralis within the same condition ($p < 0.05$), # denotes greater neuromuscular activation compared to vastus medialis within the same condition ($p < 0.05$), $ denotes greater neuromuscular activation compared to bicep femoris within the same condition ($p < 0.05$).

study may, in part, be a result of the extent of the eccentric load employed. Despite previous research eliciting kinetic output enhancements with a 105% eccentric phase load (Doan et al., 2002), other researchers have demonstrated individualising the extent of the eccentric phase load may be necessary to elicit peak kinetic outputs (Ojasto and Hakkinen, 2009a).

Due to the greater eccentric loading, eccentric phase force was greater in the AEL compared to the CL condition in the present investigation. Elevated motor unit firing rates or unique eccentric muscle action recruitment strategies were likely responsible for the greater eccentric neuromuscular activation during the AEL condition due to the greater eccentric phase loading required in this conditions (Linnamo et al., 2003). The finding of greater eccentric neuromuscular activation in the AEL condition was consistent with the acute reports from a lower-body seated flywheel AEL study, where greater eccentric force was produced in the AEL flywheel condition (Norrbrand et al., 2011). Eccentric rate of force development was not different between the two conditions. The lack of differences in eccentric rate of force development in the current study could be due to the fact that eccentric phase velocity was controlled in both conditions or because of poorer intra-participant absolute reliability of this variable (11.8-18.2%). The eccentric kinetic variable results from the current study indicate AEL squats do not cause there to be a greater rate of eccentric loading, but do involve a 7-30% greater magnitude of eccentric force compared to CL. However, it must be noted that the way the of eccentric phase was performed, in relation to 3RM eccentric phase velocity, may not necessarily replicate the eccentric phase velocity typically employed in real-world strength training practices, particularly with lighter load CL.

The lack of acute concentric neuromuscular activation differences between conditions in the current study was consistent with the results of a recent study comparing knee extensor neuromuscular activation during seated flywheel AEL compared to CL squats (Norrbrand et al., 2011). However, the flywheel AEL device employed in this previous study provides differential demands compared to free weight

CL squats as AEL flywheel squats require near maximal efforts from the first repetition of a set, are performed whilst seated, and are executed along a pre-determined path or trajectory. Therefore, several variables, in addition to extra eccentric load, that could have influenced neuromuscular activation were manipulated between conditions in this previous study. In the current study, only the addition of extra eccentric load and the way it was applied were varied between conditions. The fact that concentric neuromuscular activation did not differ between conditions in the present investigation suggest AEL does not cause additional ɑ motor neurons to be recruited in the subsequent concentric phase of an exercise, as previously hypothesised (Doan et al., 2002). In contrast to the recent acute AEL flywheel squat study where only rectus femoris neuromuscular activation increased in the eccentric phase of the exercise (Norrbrand et al., 2008), eccentric neuromuscular activation increases were reported in the current study across the measured muscles in two to three of the four sets performed. As eccentric phase load became more similar between conditions, for example in set 3, neuromuscular activation remained elevated in the knee extensor musculature. Therefore, suggesting acute anterior lower-body neuromuscular activation is effected more than posterior chain activation by weight releaser hook AEL squats. This neuromuscular control difference in the AEL condition may result as a function of weight releaser hook load distribution during a task considered to be largely a posterior chain dominant exercise. The results of the present study demonstrated no clear differences in terms of the neuromuscular activation contributions between muscles within AEL and CL conditions. Despite biceps femoris and gluteus maximus activation being 15-30% greater in the second set of the AEL condition in the concentric and eccentric phases, respectively, this was not the case during the other AEL sets. Therefore, the use of weight releaser hooks during AEL squats does not appear to effect neuromuscular activation contributions from key lower-body agonists compared to an equivalent CL exercise.

The findings of the present investigation suggest that in comparison to CL squats weight releaser hook AEL squats: (i) do not positively or negatively effect acute concentric kinetic outputs; (ii) increase the acute forces individuals are exposed to by 7-30%; (iii) do not enhance concentric phase neuromuscular activation; (iv) cause eccentric phase knee extensor neuromuscular activation to be maintained across loads; and (v) do not cause differences in neuromuscular contributions from key lower-body agonists. Therefore, given the findings from the current study exercise professionals who prescribe training interventions may want to consider the use of weight releaser AEL squats. The decision to use weight releaser hook AEL squats will be dependent on several factors including athlete/patient characteristics and training intervention goals. But it is important to note that AEL has previously been shown to equate concentric strength gains seen with AEL (Yarrow et al., 2008), produce eccentric strength gains beyond those observed with CL (Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000; Kaminski et al., 1998), and reduce injury frequency (Askling et al., 2003) when applied to lower-body musculature via methods that are less practical to implement than weight releaser hooks. Further research, following the acute findings reported within this study are required to confirm the efficacy of weight releaser hook AEL back squats on a longitudinal basis (e.g. training interventions of 4-12 weeks in duration) for concurrently benefiting both concentric and eccentric strength of the knee and hip extensors, eliciting chronic neuromuscular adaptations in these muscles, and preventing injury.

5.5 Conclusions

The findings of the present investigation suggest that weight releaser AEL squats appear to present no negative acute concentric kinetic variable responses, provide greater eccentric phase kinetic demands in terms of force production, involve greater eccentric phase knee extensor contributions across lighter and heavier loads, and do not effect the neuromuscular contributions from key agonist muscles during concentric or eccentric phases. Therefore, given these findings exercise professionals who prescribe training interventions may want to consider the use of weight releaser AEL squats depending on the characteristics and training goals of the individuals they work with. Further research is required to confirm the efficacy of weight releaser hook AEL back squats on a longitudinal basis for concurrently benefiting both concentric and eccentric strength of knee and hip extensor muscles, eliciting chronic neuromuscular adaptations in these muscles, and preventing injury.

5.6 Contribution of the chapter to the aims of the thesis

The current chapter addressed one of the main aims of the thesis by comparing acute neuromuscular and kinetic responses between AEL and CL back squats. The current chapter adds novel information to the existing literature as the results suggest that weight releaser AEL squats present no acute negative neuromuscular or kinetic effects. Therefore, in light of the equivocal training intervention findings regarding the efficacy of AEL the results of the present chapter may encourage exercise professionals who prescribe training interventions to consider the use of weight releaser hook AEL squats. In order to address the remaining aims of the thesis and further investigate how AEL may effect acute neuromuscular responses it was necessary to investigate how motor unit characteristics and maximal force production are influenced following lower-body multiple-joint AEL in the final chapter of this thesis.

CHAPTER 6

ACUTE MOTOR UNIT FIRING RATE AND COMMON DRIVE RESPONSES TO ACCENTUATED ECCENTRIC LOAD BACK SQUATS

Balshaw TG, Pahar M, Chesham RA, Donald N, Hunter AM.

6.1 Introduction

Motor unit firing rate was shown to decrease in later-recruited motor units in response to single-joint AEL in Chapter 4, whilst common drive was not influenced following either AEL or CL interventions. However, it is unclear if the same motor unit firing rate and common drive responses observed in Chapter 3, in a single-joint resistance exercise, would occur for a multiple-joint resistance exercise. Investigating these responses in a multiple-joint resistance exercise model may provide further mechanistic insight into how AEL may potentially contribute to enhanced chronic strength adaptations (Selvanayagam et al., 2011). Single-joint resistance exercise has application for maintaining strength in an injured limb through cross-education (Shima et al., 2002) and for rehabilitation purposes (Schmitz and Westwood, 2001). However, multiple-joint free weight resistance exercise is considered to place greater demands on the neuromuscular and proprioceptive systems. The neuromuscular and proprioceptive systems are likely placed under greater demands during free weight resistance exercise due to: (i) the greater muscle mass involved; (ii) the coordination required between multiple muscles; and (iii) the need to stabilise the body in response to gravity, ground reaction forces, and momentum (Maddalozzo and Snow, 2000). In addition the chronic strength adaptations that occur with free weight resistance exercise are thought to be more transferable to real-world daily and sporting activities

(Kraemer and Ratamess, 2004). Accordingly, the decision to compare acute motor unit firing rate and common drive responses following the AEL and CL interventions detailed in Chapter 5 was made.

Previously, transcranial magnetic stimulation measurements have been employed following acute bouts of upper-body strength and ballistic type resistance exercise to provide information regarding central nervous system and neuromuscular responses. Although transcranial magnetic stimulation has been used to investigate both chronic adaptations (Griffin and Cafarelli, 2007; Carroll et al., 2002) and acute responses (Selvanayagam et al., 2011) to resistance exercise, the emergence of new hardware and software, namely high density EMG (De Luca et al., 2006), now provides the opportunity to non-invasively procure firing rate data from a high yield of single motor units (~40) (Beck et al., 2011; Nawab et al., 2010). Determining how centrally influenced variables such as motor unit firing rate and correlated motor unit activity (e.g. common drive) are acutely influenced in a large number of single motor units following resistance exercise may further current understanding of how different types of resistance exercise elicit chronic neural adaptations.

The decomposition of surface EMG makes non-invasively investigating motor unit firing rate variables possible. Importantly, high density EMG measures may prove to be more sensitive to subtle responses or adaptations in common drive following acute resistance exercise bouts or chronic resistance exercise training interventions (Carroll et al., 2011). In addition, the high motor unit yield from high density EMG measurements provides new opportunities to investigate the responses of motor unit subpopulations, which are characterised as having different firing rates (De Luca and Hostage, 2010; De Luca and Erim, 1994; De Luca et al., 1982). Intra-muscular wire electrode studies have previously shown motor unit firing rate to increase following acute resistance exercise (Kamen and Knight, 2004; Van Cutsem et al., 1998), whereas the timing of firings from a motor unit in relation to those of another unit can also reveal acute post-resistance exercise neural adjustments (De Luca et al., 2006).

Cross-sectional studies using fine wire electrodes have reported greater common drive in strength-trained individuals in comparison to skill-trained individuals, with control group participants displaying intermediate levels of common drive (Semmler and Nordstrom, 1998). Therefore, an increase in common drive may be one of the neuromuscular adaptations responsible for chronic strength adaptations (Carroll et al., 2011; Semmler and Nordstrom, 1998). In contrast, other cross-sectional research findings dismiss increased common drive as a strength training adaptation (De Luca et al., 1982). Although such studies provide invaluable information for understanding neural adaptations to strength training, the conclusions from these studies are restricted to a limited number of motor units from each different training population (Semmler and Nordstrom, 1998).

AEL has previously been shown to increase the CSA of type IIX, but not other muscle fibre types. Whether, different acute neural responses occur between motor unit populations in a similar way to the reported morphological adaptations following AEL is uncertain. The findings of Chapter 4 (section 4.3.1) suggest this may be the case in a single-joint model, but it is unclear whether motor unit firing rate responds similarly in a multiple-joint model. The comparison of acute motor unit firing rate and common drive responses between AEL and CL, determined from high density EMG, may provide new mechanistic insight regarding how each of these types of resistance exercise influence neuromuscular control. Therefore, the purposes of the study were threefold; firstly, to compare motor unit firing rate and common drive responses after lower-body multiple-joint AEL and CL; secondly, to examine differences in lower limb maximal force production following AEL and CL back squats; and thirdly, to assess the between test day reliability and inter-individual variability of motor unit firing rate analysis during a lower-body isometric trapezoid force trace effort. In Chapter 4 of the thesis it was established that the firing frequency of earlier-recruited, mid-recruited, and later-recruited vastus lateralis motor units had the greatest absolute reliability towards the end of the plateau phase of the isometric trapezoid force trace effort, when the effort was performed at a 70° knee joint angle on the Biodex 3 dynamometer. It was deemed appropriate to analyse vastus lateralis firing rate reliability in the current study as isometric trapezoid force trace efforts were performed on a custom-built dynamometer with a different knee joint angle and at a lower isometric force level compared to Chapter 4. A lower force level was employed as a result of the demands of the acute multiple-joint AEL and CL interventions used.

6.2 Methods

6.2.1 Participants

Eight of the ten males who were described in Chapter 5 (section 5.2.1) completed the additional neuromuscular measurements detailed within this chapter. Due to technical difficulties it was not possible to obtain after-intervention MVC or isometric trapezoid force trace effort measures for two of the participants who took part in Chapter 5.

6.2.2 Procedures

Knee extension maximal voluntary isometric contractions

Knee extension MVCs were performed with the participant’s non-dominant leg on a custom-built dynamometer (Figure 6.1), consisting of a strain gauge (Load Cell 700-001K2 S-Beam, Richmond Industries, Reading, UK) attached to a knee extension machine frame. During MVCs participants were firmly restrained with adjustable straps (Master Lock Company, Wisconsin, USA) at the shoulders, waist, and non-involved leg to minimise extraneous bodily movements. During MVCs the seat settings of the knee extension frame and the height at which the strain gauge was attached to the frame were standardised and recorded for each participant. This configuration allowed the ankle cuff attached to the strain gauge to be positioned above the lateral epicondyle of the participant’s involved leg, at a 90° knee joint flexion angle (0° equalling full knee


[redacted]

Figure 6.1 Custom-built knee extension dynamometer. Broken line box denotes strain gauge unit.

extension; Figure 6.1). A 90° knee joint angle was selected as it allowed a horizontal line of pull on the strain gauge unit from its point of attachment to the knee extension frame.

The strain gauge was calibrated in accordance with manufacturer guidelines (1 Newton = 0.0082 V). An amplifier unit (AMP3, Richmond Industries, Reading, UK) allowed voltage data from the strain gauge to be collected during MVCs with an integrated software package (EMGworks® 4.0 Acquisition software, Delsys, Boston, USA). One min recovery periods were employed between MVCs. Participants were instructed to produce a maximal force as quickly as possible from the signal to start the MVC, prior to each MVC. Intense verbal encouragement was provided to participants during all MVCs (Campenella et al., 2000).

Isometric knee extension trapezoid force trace effort

Isometric knee extension trapezoid force trace efforts were also performed on the custom-built dynamometer with the non-dominant leg at a 90° knee joint angle. The isometric trapezoid effort involved a 4 s quiescent period a, linear 6 s ramp up in force from 0% to 60% of peak MVC force, a 10 s holding force levels constant at 60% of peak MVC force, and then a linear 6 s ramp down from 60% to 0% of MVC peak force and a final 4 s quiescent period (Figure 6.2). Participants met the required isometric trapezoid force trace via visual feedback displayed on a computer screen. As the AEL and CL interventions within the present investigation involved high force levels it was critical to investigate motor unit firing rate and common drive responses at as high isometric force level as possible. Performing the plateau phase of the isometric trapezoid force trace at the highest force level possible was intended to ensure higher threshold motor units that were likely to be recruited during interventions would also be active during isometric trapezoid force trace efforts. A 60% plateau phase was selected as pilot work conducted for the study suggested this level of force could be maintained during isometric trapezoid force trace efforts completed after the AEL and CL interventions.

6.2.3 Experimental protocol

Participants completed the same before-experimental session controls and experimental protocols that were detailed in Chapter 5 (section 5.2.3). The initial two sessions were used to assess 3RM back squat strength as described in Chapter 5 (section 5.2.2) and familiarise participants with the tasks to be performed in the final two experimental testing sessions. During the familairisation session participants practiced as many as five isometric knee extension trapezoid force trace efforts in order to ensure they could accurately follow the force trace during experimental condition test sessions. Participants practiced the isometric trapezoid force trace in addition to the familiarisation session items described in Chapter 5 (section 5.2.3). In the final two laboratory visits participants completed a single experimental condition on

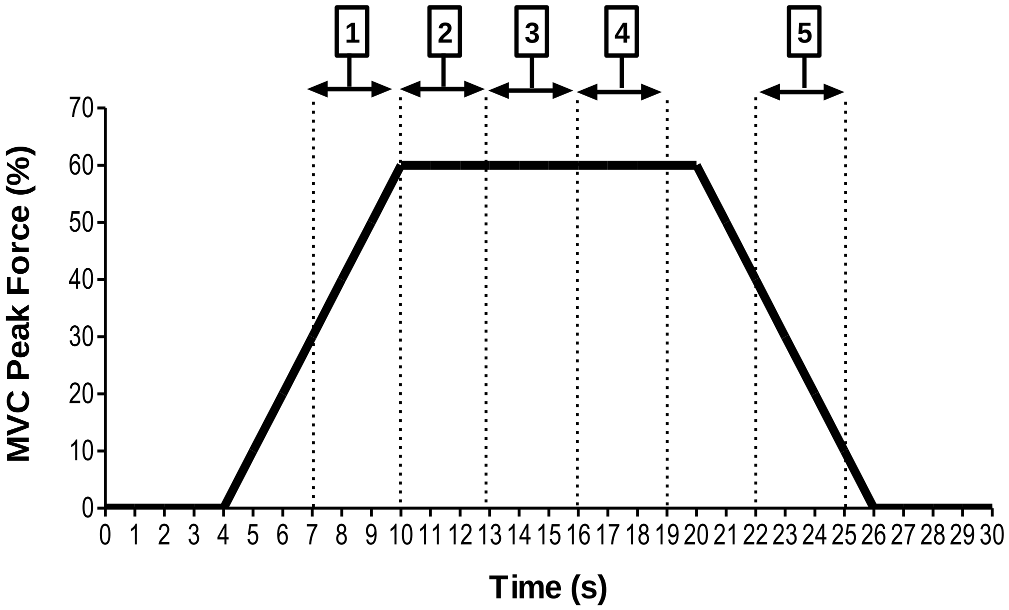


Figure 6.2 Knee extension isometric trapezoid effort force trace (denoted as a percentage of MVC peak force) with illustration of the identified time periods that were used for motor unit firing rate analysis: (1) ascent or recruitment phase; (2-4) plateau or constant force phase; and (5) descent or derecruitment phase.

each test day in randomised order (Figure 6.3). A minimum of 5 d separated each experimental test day.

On experimental condition test days participants completed three 5 s knee extension MVCs and a single isometric trapezoid force trace effort before completing CL or AEL knee extension efforts. The recovery period between each isometric effort during the before- and after-intervention measures was set at 1 min. In order to prepare for the before-intervention MVCs a standardised warm-up consisting of three 5 s isometric efforts at 75% of perceived maximum was conducted. The highest torque obtained during the three before-intervention MVCs was taken as the peak force MVC and used to prescribe force levels during the before and after-intervention trapezoid force trace efforts. Five min after the before-intervention isometric trapezoid force trace participants completed warm-up, preparatory, and experimental condition back squat sets as described in Chapter 5 (section 5.2.3). After-intervention measures involved the performance of a further three MVCs and a single isometric trapezoid force trace effort.

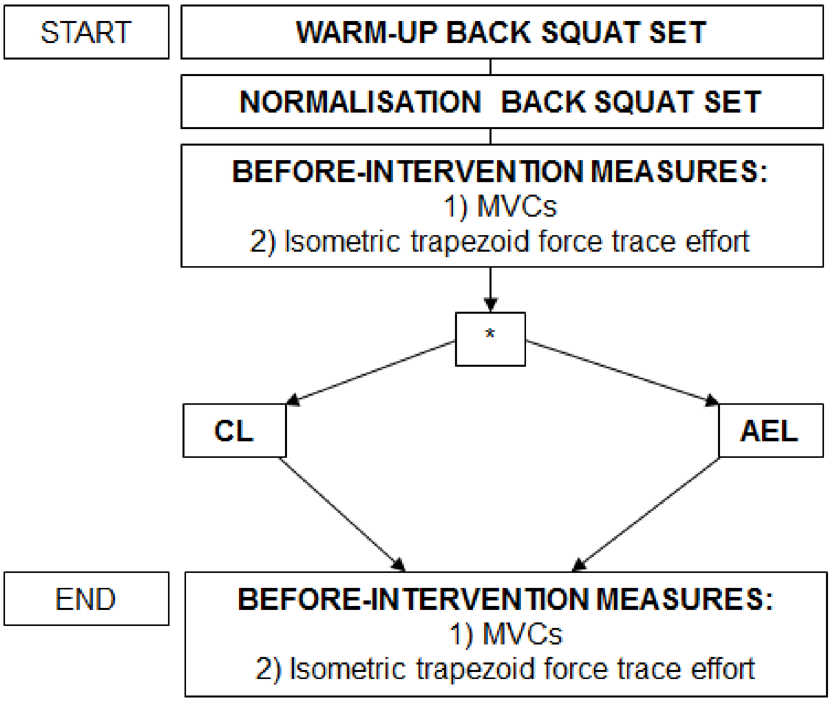


Figure 6.3 Experimental condition protocol. * denotes randomisation of experimental conditions.

After-intervention MVCs commenced 5 min after the end of the final experimental condition back squat set.

6.2.4 High density EMG and MVC force data collection

Vastus lateralis high density EMG was measured as described in Chapter 4 (section 4.2.4). Vastus lateralis EMG and force data from the strain gauge were synchronously recorded via software (EMGworks® 4.0 Acquisition software, Delsys, Boston, USA) integrated with the EMG system. Voltage data quantifying force from the strain gauge attached to the custom-built dynamometer was amplified (AMP3, Richmond Industries, Reading, UK) prior to being recorded.

6.2.5 EMG signal decomposition, analysis and accuracy

Vastus lateralis high density EMG was decomposed as detailed in Chapter 4 (section 4.2.5). Motor unit firing rate data were analysed as described earlier (section

4.2.5). Common drive was quantified as described in Chapter 4 (section 4.2.5). The number of detected motor units during each isometric trapezoid force trace effort was extracted from the EMGworks® Analysis software and analysed as detailed in Chapter 4 (section 4.2.5). Decomposition accuracy was assessed as described earlier (section 4.2.5).

6.2.6 Statistical analysis

Statistical analyses to assess motor unit firing rate reliability (absolute and relative reliability) and inter-participant variability were conducted as described in Chapter 4 (section 4.2.6). Time-point (before-intervention *vs.* after-intervention) x condition (AEL *vs.* CL) repeated measures analysis of variance were conducted to assess motor unit firing rate, cross-correlation coefficients, the maximum number of motor units detected, and peak MVC force differences between conditions.

6.3 Results

6.3.1 Motor unit firing rate analysis, number of detected motor units, and MVC force.

As time phase four demonstrated “acceptable”-“good” absolute reliability (assessed via intra-participant coefficient of variation) across motor unit populations (earlier-recruited, mid-recruited, later-recruited, and overall), this period alone was used for motor unit firing rate analysis. No differences in firing rate occurred between conditions for earlier-recruited (p= 0.768, f= 0.09), mid-recruited (p= 0.670, f= 0.20), or later-recruited (p= 0.226, f= 1.77) motor unit populations (Figure 6.4). Time-point effects were not detected for earlier-recruited (p= 0.768, f= 0.09), mid-recruited (p= 0.670, f= 0.20), or later-recruited (p= 0.226, f= 1.77) motor unit firing rates (Figure 6.4). Condition-time-point interactions were also absent for the firing rates of earlier-recruited (p= 0.464, f= 0.60), mid-recruited (p= 0.898, f= 0.02), and later-recruited (p= 0.560, f= 0.38) motor units (Figure 6.4). No differences in the maximum number of detected motor units were detected between conditions (p= 0.960, f= 0.00; Figure 6.5). Additionally, no time-point (p= 0.966, f= 0.00) or condition-time-point interaction (p= 0.598, f= 0.31) effects were observed for the maximum number of detected motor units during isometric trapezoid efforts. MVC peak force demonstrated no condition (p= 0.974, f= 0.00), time-point (p= 0.491, f= 0.52), or condition-time-point interaction (p= 0.199, f= 1.96) effects (Figure 6.5).

6.3.2 Common drive

Due to processing difficulties with a time-point of one of the participants an *n* of 7 was included for common drive analysis. As time phase four of the isometric trapezoid force trace efforts demonstrated the greatest absolute reliability (assessed via intra-participant coefficient of variation) across the largest number of motor unit populations (earlier-recruited, mid-recruited, later-recruited, and overall motor unit firing rates), this plateau phase alone was used for common drive analysis. No differences in the distribution of the common drive frequency histograms were detected from before- to after-intervention measures regardless of the condition completed (Figure 6.6). Peak cross-correlation histogram frequency occurred in the range of 0.6 to 0.7 in all conditions. Similarly no differences in maximum (p= 0.304, f= 1.26; Figure 6.7 A) and mean (p= 0.341, f= 1.07; Figure 6.7 B) peak cross-correlation coefficients were detected between conditions. Time-point effects were not detected for maximum (p= 0.981, f= 0.00; Figure 6.7 A) and mean (p= 0.692, f= 0.17; Figure 6.7 B) peak cross-correlation coefficient values. Condition-time-point interaction effects were observed for maximum (p= 0.028, f= 8.24; Figure 6.7 A), but not mean (p= 0.990, f= 0.00; Figure 6.7 B) peak cross-correlation coefficient values.

6.3.3 Decomposition accuracy

Before-intervention isometric trapezoid force trace efforts displayed 93.2 ± 2.1% accuracy in the CL and 94.3 ± 1.7% accuracy in the AEL condition. After-intervention isometric trapezoid force trace efforts displayed 93.6 ± 2.2% accuracy in the CL and 93.8 ± 2.2% accuracy in the AEL condition. Before-intervention isometric trapezoid force trace efforts demonstrated 1.7 ± 0.6 errors•s^{-1} and 1.5 ± 0.4 errors•s^{-1} in the CL and AEL conditions, respectively. After-intervention isometric trapezoid force trace efforts demonstrated 1.8 ± 0.6 errors•s^{-1} and 1.7 ± 0.8 errors•s^{-1} in the CL and AEL conditions, respectively.

6.3.4 Absolute reliability, relative reliability, and inter-participant variability for motor unit firing rate data

Time phase four, three, and five displayed the lowest intra-participant coefficient of variation for earlier-recruited, mid-recruited, and later-recruited motor units, respectively (Table 6.1). Similar intra-participant coefficient of variation was demonstrated for overall motor unit firing rate in time phases four and five. The narrowest limits of agreement values were displayed for time phase five, three, and four for earlier-recruited, mid-recruited, and later-recruited motor units, respectively (Table 6.1). All intraclass correlation coefficient scores were classified as “poor” (Table 6.2), out of these values the best intraclass correlation coefficient values were displayed for earlier-recruited motor units, mid-recruited motor units, later-recruited motor units, and overall firing rate in time phases one, two, five and five, respectively. Common (<12.0% inter-participant coefficient of variability) motor unit firing rates were not displayed in any of the motor unit populations (Table 6.2). Time phase four consistently displayed the lowest or second lowest intra-participant coefficient of variation values across motor unit populations.

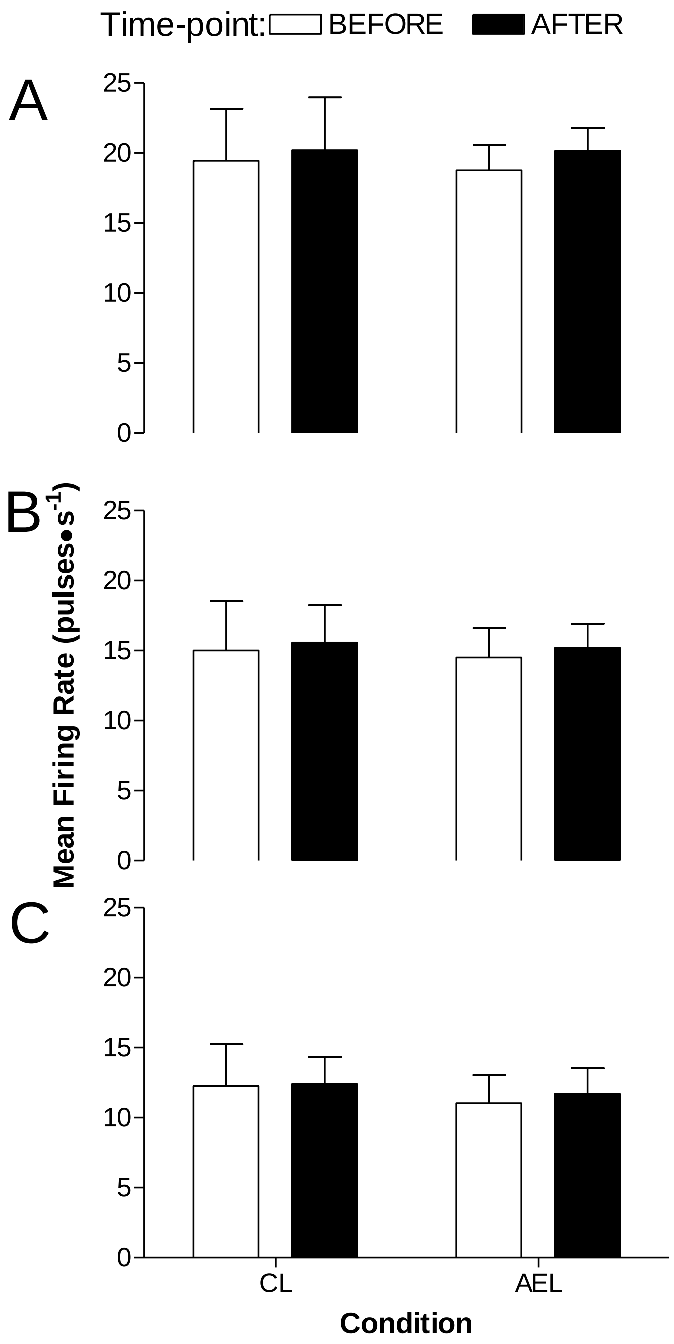


Figure 6.4 Mean vastus lateralis firing rate (pulses•s^{-1}) during the selected region of the constant force phase of the submaximal knee extension isometric force trace effort for: (A) earlier-recruited; (B) mid-recruited; and (C) later-recruited motor units before and after AEL and CL conditions.

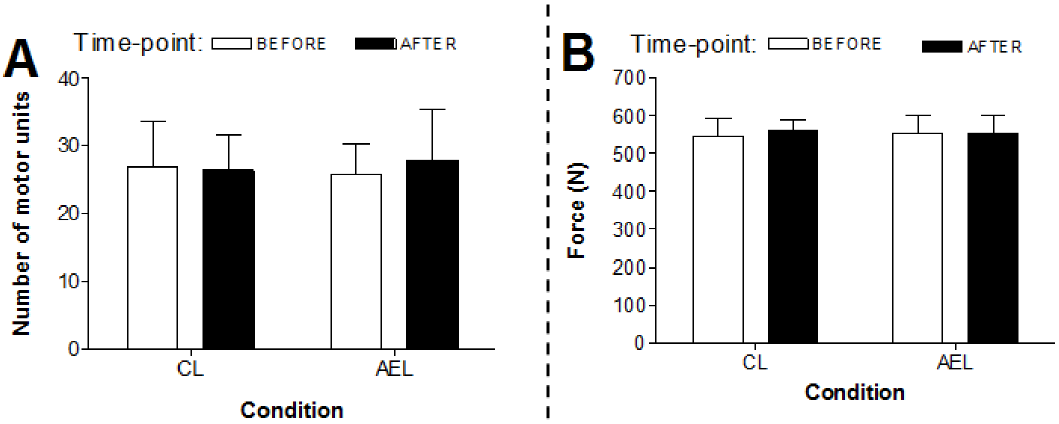


Figure 6.5 Maximum number of detected motor units during isometric trapezoid force efforts (A) and peak force during MVC knee extension efforts (B) in AEL and CL conditions.

6.4 Discussion

6.4.1 Motor unit firing rate, common drive, and force production responses

The results of the study demonstrated no between condition differences for: (i) motor unit firing rate; (ii) the number of active detected motor units; or (iii) MVC peak force when acute lower-body multiple-joint free weight AEL and CL were compared. The maximum peak cross-correlation coeffients was decreased in the CL condition following interventions, but other common drive measures were unaffected. The findings of the current study indicate that differential acute neuromuscular responses do not occur in response to a multiple-joint lower-body AEL model. Absolute reliability across different motor unit populations was “acceptable”-“good” in time phase four, the final part of the plateau phase of the submaximal isometric trapezoid effort. Therefore, both motor unit firing rate and common drive analysis were calculated from time phase four.

Previously, AEL has been shown to increase type IIX muscle fibre cross sectional area during a single-joint 6 week resistance training intervention study (Friedmann-Bette et al., 2010). Therefore, indicating AEL influences the morphological charactersitics of later-recruited muscle fibers. The findings from the present investigation differ from those of the single- joint AEL intervention detailed in Chapter 4,

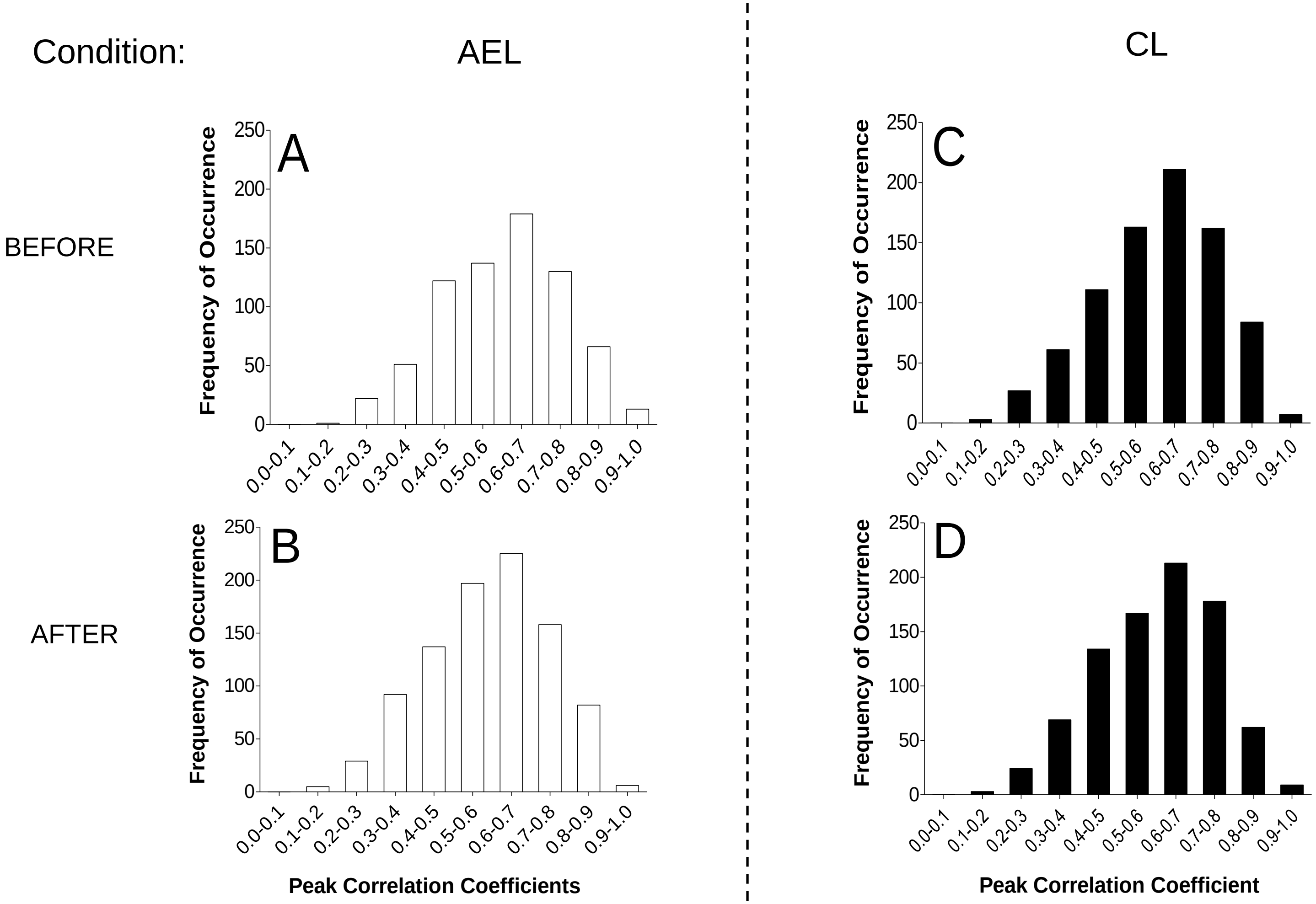


Figure 6.6 Histograms of the maximum cross-correlation coefficients between each pair of motor units that were cross-correlated across all participants before and after AEL and CL conditions.

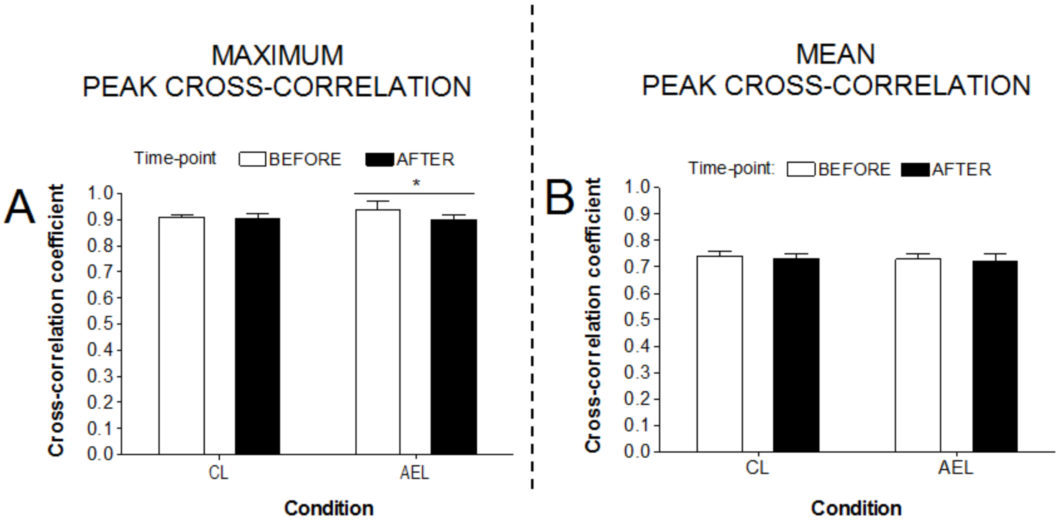


Figure 6.7 Maximum (A) and mean (B) peak cross-correlation coefficients in AEL and CL conditions.

and suggest that lower-body multiple-joint free weight AEL does not effect neural responses or place additional demands on later-recruited motor units, compared to CL. This may indicate that the isolated nature of single-joint resistance exercise effects the later-recruited motor units of the vastus lateralis differently compared to during multiple-joint resistance exercise where coordination of muscles across joints allows a given resistance exercise to be performed. The motor unit firing rates of earlier-recruited motor units in the present investigation were, as previously reported in Chapter 4 and numerous other studies, greater than those of later-recruited motor units (De Luca and Hostage, 2010; De Luca and Erim, 1994; De Luca et al., 1982). As in Chapter 4, the vastus lateralis firing rates reported in the current study are less than those reported in previous work (Roos et al., 1999). However, similar average vastus lateralis firing rates (~20 pulses•s^{-1}) have been reported in earlier research, both before- and after-resistance exercise training interventions at 50-60% (Stock et al., 2012) and 75% (Pucci et al., 2006) of MVC peak force, as the firing rates of earlier-recruited motor units in the present study.

Table 6.1 Summary of vastus lateralis firing rate absolute reliability measures for earlier-recruited, mid-recruited, and later-recruited motor units. The values in boxes denote the time phase with the greatest reliability for each variable for each motor unit tertile.

		95% Lower limits of agreement	95% Upper limits of agreement	Intra-participant coefficient of variation			Coefficient of variation descriptor
		Mean	Mean	Mean	±	SD	
Motor unit tertile	Time phase						
Earlier-recruite	1	-11.6	9.7	28.6	±	20.9	Unacceptable
	2	-9.0	8.4	11.9	±	10.1	Acceptable
	3	-8.8	8.4	10.8	±	9.8	Good
	4	-8.0	8.0	***10.7***	**±**	***8.6***	Good
	5	**-7.9**	**7.1**	11.6	±	8.2	Good
Mid-recruited	1	-9.2	10.7	101.0	±	42.8	Unacceptable
	2	-10.7	10.2	28.4	±	23.2	Unacceptable
	3	**-7.1**	**6.7**	***12.4***	**±**	***12.1***	Acceptable
	4	-7.6	7.3	14.3	±	11.2	Acceptable
	5	-13.0	10.6	32.3	±	30.5	Unacceptable
Later-recruited	1	-4.8	6.9	17.7	±	50.0	Acceptable
	2	-12.1	13.8	13.8	±	39.0	Acceptable
	3	-9.7	11.3	38.8	±	32.1	Unacceptable
	4	***-5.6***	***6.4***	2.1	±	6.0	Good
	5	-10.2	7.2	***0.5***	**±**	***1.3***	Good
Overall	1	-8.5	9.7	27.9	±	13.4	Unacceptable
	2	-8.6	7.8	17.1	±	13.6	Acceptable
	3	-7.6	6.9	12.7	±	11.9	Acceptable
	4	-6.7	6.8	12.3	±	9.3	Acceptable
	5	**-5.6**	**5.5**	***11.9***	**±**	***8.2***	Good

Table 6.2 Summary of vastus lateralis firing rate relative reliability and inter-participant variability measures for earlier-recruited, mid-recruited, and later-recruited motor units. The values in boxes denote the time phase with the greatest reliability for each variable for each motor unit tertile.

		Inter-participant coefficient of variation			Intraclass correlation coefficient			
		Mean	±	SD	Mean	LCI*	UCI**	Descriptor
Motor unit tertile	Time phase							
Earlier-recruited	1	42.7	±	16.0	***-0.30***	***-0.81***	***0.46***	Poor
	2	16.9	±	6.1	-0.63	-0.91	0.07	Poor
	3	16.2	±	5.1	-0.57	-0.90	0.16	Poor
	4	***15.2***	***±***	***3.5***	-0.47	-0.86	0.29	Poor
	5	15.6	±	5.0	-0.56	-0.89	0.17	Poor
Mid-recruited	1	144.7	±	31.5	-0.04	-0.69	0.64	Poor
	2	46.9	±	1.8	***0.07***	***-0.63***	***0.70***	Poor
	3	***19.0***	***±***	***1.2***	-0.14	-0.74	0.58	Poor
	4	19.5	±	2.5	-0.23	-0.78	0.51	Poor
	5	36.9	±	7.6	-0.05	-0.69	0.64	Poor
Later-recruited	1	215.9	±	23.2	-0.03	-0.68	0.65	Poor
	2	96.3	±	7.5	-0.31	-0.81	0.45	Poor
	3	44.6	±	5.8	-0.22	-0.77	0.53	Poor
	4	***22.2***	***±***	***3.0***	-0.06	-0.70	0.63	Poor
	5	73.2	±	14.7	***-0.10***	***-0.72***	***0.61***	Poor
Overall	1	26.6	±	15.9	-0.07	-0.70	0.63	Poor
	2	24.2	±	0.6	0.16	-0.57	0.74	Poor
	3	18.8	±	0.6	0.11	-0.60	0.73	Poor
	4	16.9	±	0.7	0.15	-0.57	0.74	Poor
	5	***16.4***	***±***	***3.7***	***0.21***	***-0.53***	***0.77***	Poor

* lower confidence interval, ** upper confidence interval.

Two of the three measures of common drive were unchanged following AEL or CL interventions. The fact that common drive was largely unaffected by either the CL or AEL intervention provides indirect support for the concept that changes in common drive may not be required for increases in strength (Kidgell et al., 2006; Duchateau et al., 2006). Alternatively, measure of common drive may not be acutely responsive in a population where adaptations in this variable may have already occurred, due to strength training history (Semmler and Nordstrom, 1998). The findings of the current chapter provide indirect support for research suggesting alterations in common drive do not occur as a result of strength training (Beck et al., 2011; De Luca et al., 1982). However, other research conducting cross-sectional investigations of skill-trained, strength-trained, and control participants indicate common drive adaptations do occur in individuals with divergent training backgrounds (Semmler and Nordstrom, 1998). The finding that common drive was unchanged following AEL was consistent with other cross-correlational analysis research that used a greater volume of eccentric resistance exercise to induce muscle damage (Beck et al., 2012), but in contrast to the findings of other studies (Dartnall et al., 2011; Dartnall et al., 2008). The disparity in findings between studies regarding common drive may be due to differences in the exercise protocol conducted, the type of electrode employed (high density EMG electrode *vs.* intra-muscular wire electrode) or the way cross-correlation analyses were conducted (Dartnall et al., 2011; Dartnall et al., 2008). It is important to note that the neuromuscular measures employed in the current investigation were performed during an isometric task and therefore may not reflect the acute motor unit firing rate or common drive responses during dynamic muscle actions, following AEL and CL conditions (Semmler et al., 2002). The contrasting common drive results in the current study indicate further research may be required to elucidate how AEL and CL influence common drive on a longitudinal basis, such as following a training intervention programme.

The motor unit firing rate results produced from the current study are consistent with previous upper-body acute AEL studies, where neuromuscular measures did not demonstrate differential concentric neuromuscular responses during AEL compared to CL (Ojasto and Hakkinen, 2009a; Ojasto and Hakkinen, 2009b). However, the results presented in the current study oppose the decrease in the motor unit firing rate of later-recruited motor units observed in Chapter 4 during a single-joint lower-body AEL model. The difference in findings between the current chapter and Chapter 4 may reflect differences in the resistance exercise model, loading, or training volume employed in each intervention. The results of the current study suggest that free weight multiple-joint lower-body AEL does not lead to differential acute neuromuscular responses, as only one of three common drive measures were effected. However, given the paucity of neuromuscular measures performed within the AEL training intervention literature it may still be worthwhile to investigate common drive adaptations during and following a longitudinal multiple-joint free weight lower-body AEL training study. To date, only one longer-term AEL training intervention study using a lower-body free weight multiple-joint resistance exercise model has been conducted (Yarrow et al., 2008). However, neuromuscular measures were not performed within the study and only concentric strength adaptations were assessed. Two short-term resistance machine-based AEL training intervention studies have attributed superior strength gains to differential neuromuscular adaptations, with regard to neuromuscular activation levels (Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000). Although the findings within the present study largely indicate no differences in acute neuromuscular responses of the knee extensors, longer duration AEL training studies employing measures to quantify neuromuscular adaptation as well as eccentric and concentric strength are still required. Such studies would allow conclusions to be made on the efficacy of AEL for achieving superior chronic strength adaptations (either concentric, eccentric or both types of strength).

6.4.2 Motor unit firing rate absolute, relative, and inter-participant reliability

The quality and reliability of the data in the current chapter are demonstrated by the “reconstruct and test” analysis (Nawab et al., 2010). The “reconstruct and test” system has previously been validated and provides quantification of signal decomposition accuracy to ensure users can focus on analysing accurate data (De Luca and Nawab, 2011; De Luca et al., 2006). Similarly to Chapter 4 the firing rate of earlier-recruited, mid-recruited, and later-recruited motor units had the greatest absolute reliability towards the end of the plateau phase of the isometric trapezoid force trace effort. This finding may be due to stabilisation of motor unit firing rate with time during the sustained isometric contraction (Contessa et al., 2009; Bigland-Ritchie et al., 1983). The “poor” between-day relative reliability of the vastus lateralis firing rates for each motor unit population may be a function of the homogenous training status of the participant sample. In Chapter 4 greater relative reliability was observed for recreational resistance exercising individuals, suggesting vastus lateralis motor unit firing rate may become more similar with increasing strength levels. Such an adaptation may therefore lead to greater within-participant than between-participant variance for motor unit firing rate and consequently impact relative reliability values (Larsson et al., 1999). Indeed, reduced motor unit firing rate variability has been demonstrated following resistance exercise training in older adult populations (Laidlaw et al., 2000). However, previously no change in firing rate variability has been demonstrated in younger individuals in response to resistance exercise (Laidlaw et al., 2000).

6.5 Conclusions

The findings of the current study indicate that multiple-joint lower-body AEL does not acutely influence motor unit firing rate and only influenced one of three different common drive variables. Vastus lateralis later-recruited motor unit firing rates did not decrease after the AEL intervention, as was the case following the single-joint model employed in Chapter 4. This suggests that the type of resistance exercise model used may influence acute motor unit firing rate responses. The lack of response in two out of three common drive measures in a large population of motor units following AEL or CL interventions, lends indirect support to suggestions from both cross-sectional and training intervention research that alterations in common drive may not occur following resistance exercise. Further research should be conducted in untrained populations to conclude if motor unit firing rate and common drive are as equally unresponsive on both acute and longitudinal scales, in order to assess the efficacy of AEL for clinical and general populations without a history of strength training.

6.6 Contribution of the chapter to the aims of the thesis

The current chapter addressed the final aims of the thesis by comparing common drive and motor unit firing rate responses after lower-body multiple-joint AEL and CL. The results of the present study indicate acute motor unit firing rate responses do not occur following either AEL or CL back squats and that the majority of common drive measures are unresponsive following both CL and AEL squats. Along with the findings of Chapter 4, these results add to the results of previous studies investigating acute neural responses via the use of transcranial magnetic stimulation. The results of the current study suggest training status and exercise familiarity may influence the acute motor unit characteristic responses observed as neither AEL or CL squats acutely influenced motor unit firing rate and the majority of common drive measures were unaffected other than maximum peak cross-correlation coefficient following CL squats.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Thesis summary

Training interventions comparing AEL and CL have been conducted to assess the efficacy of AEL for enhancing chronic strength adaptations. AEL has been shown to elicit greater strength gains than CL (Norrbrand et al., 2008; Friedmann et al., 2004; Brandenburg and Docherty, 2002; Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000; Kaminski et al., 1998). However, other AEL training intervention studies have demonstrated the strength adaptations observed to equate those seen with CL (Friedmann-Bette et al., 2010; Yarrow et al., 2008; Barstow et al., 2003; Godard et al., 1998; Ben-Sira et al., 1995; Nichols et al., 1995). The greater chronic strength gains that have been reported with AEL have been attributed to both neuromuscular (Hortobagyi et al., 2001a; Hortobagyi and Devita, 2000) and morphological (Norrbrand et al., 2008; Friedmann et al., 2004) adaptations. In contrast, other longer duration AEL training intervention studies have not reported morphological changes in either CL or AEL conditions, despite greater chronic strength adaptations occurring with AEL (Norrbrand et al., 2008; Brandenburg and Docherty, 2002). Therefore, neuromuscular adaptations seem to be a crucial factor in the superior strength and power improvements reported with AEL. However, besides two AEL studies of short duration (7 d) employing intensified training, no measures of neuromuscular adaptation have been performed during longer duration AEL interventions. Therefore, a lack of information is currently available regarding how AEL may differentially affect neuromuscular control when compared to CL. Furthermore, the equivocal findings regarding the efficacy of AEL make it difficult for exercise professionals to decide whether or not to employ AEL with their athletes or patients, and during which training phase this type of resistance exercise could be implemented. The novel data presented in this thesis contributes new knowledge to the AEL research literature by investigating how AEL acutely effects neuromuscular control. The findings presented provide both mechanistic information and information to guide the exercise prescription of practitioners.

7.1.1 Chapter 2: Evaluation of EMG normalisation methods for the back squat

Previously no studies had compared the reliability of different surface EMG normalisation methods for the barbell free-weight back squat. This methodological study was necessary in order to later compare neuromuscular control between AEL and CL during a widely used resistance exercise. The study had three aims: (i) to evaluate the reliability of maximal isometric and submaximal dynamic EMG normalisation methods for concentric and eccentric phase neuromuscular activation during the back squat resistance exercise; (ii) to examine the sensitivity of each method in detecting statistical differences between neuromuscular activation levels in incremental intensity dynamic back squat exercise sets; and (iii) to assess the extent of neuromuscular activation heterogeneity in a group of strength-trained individuals experienced in performing the back squat exercise.

In summary, the results of the study showed:

(i) The 80% of 3RM dynamic back squat EMG normalisation method produced the greatest absolute reliability for the vastus lateralis and biceps femoris muscles during both concentric and eccentric phases of the back squat.

(ii) The MIS normalisation method displayed the greatest relative reliability for both muscles during eccentric and concentric phases.

(iii) The 60% of 3RM and 70% of 3RM dynamic back squat EMG normalisation methods were the most sensitive for the vastus lateralis and biceps femoris during eccentric and concentric phases.

(iv) Compared to unnormalised EMG the use of the dynamic normalisation methods (60% of 3RM, 70% of 3RM, and 80% of 3RM) reduced inter-participant variability during both muscle action phases for the vastus lateralis and biceps femoris.

(v) The use of the maximal isometric normalisation methods (MVC and MIS) reduced inter-participant variability compared to unnormalised EMG during both muscle action phases for the vastus lateralis, but not the biceps femoris.

In conclusion, dynamic EMG normalisation methods for the back squat were demonstrated to be superior compared to maximal isometric methods when considering absolute reliability and sensitivity. Additionally, dynamic EMG normalisation methods for the back squat reduced inter-participant variability compared to unnormalised EMG for both muscle actions and muscles. In contrast maximal isometric methods only reduced inter-participant variability for the biceps femoris. Therefore, researchers conducting studies concerning absolute reliability, sensitivity, and inter-participant variability measures should use submaximal dynamic tasks as opposed to maximal isometric normalisation methods. The results of the study also meant a submaximal dynamic normalisation task could be used in Chapter 5 of the thesis for the purposes of comparing neuromuscular control during AEL and CL back squats.

7.1.2 Chapter 3: Acute neuromuscular, kinetic, and kinematic responses to lower-body single-joint AEL

Previously, no lower-body AEL studies synchronously measuring neuromuscular activation, kinetic, and kinematic responses have been conducted. In light of the equivocal AEL *vs.* CL training intervention strength adaptation results that have been reported it is difficult for practioners to decide upon whether or not to employ AEL with their athletes or patients, during which training phase this resistance exercise variant could be implemented, and how AEL may acutely effect neuromuscular control compared to CL. Determining the acute neuromuscular, kinetic, and kinematic responses to knee extension AEL would inform the prescription or refinement of resistance training programmes for individuals within athletic and rehabilitative training settings. Therefore, the second study of the thesis study had the following aims: (i) to examine differences in acute neuromuscular, kinetic, and kinematic responses between AEL and CL conditions during unilateral dynamometer-based knee extension exercise; (ii) to assess both rate of torque development and muscle contractile properties following AEL and CL; and (iii) to investigate the influence of eccentric phase velocity (and time under tension) on the parameters detailed in the first two aims of the study.

In summary, the results of the study showed:

(i) That there were no differences in concentric neuromuscular, kinetic, or kinematic variables during knee extension efforts between AEL and CL conditions.

(ii) That no differences in rate of torque development or tensiomyography measures occurred between conditions.

(iii) That elevated eccentric neuromuscular activation occurred in AEL conditions at both investigated velocities, without any decrement in neuromuscular, kinetic, or kinematic responses in the subsequent concentric phase.

In conclusion, there does not appear to be any disadvantages of completing acute single-joint knee extensor AEL in terms of neuromuscular function or muscle contractile characteristics. Independent of eccentric phase velocity AEL required elevated eccentric neuromuscular activation, but equated the concentric neuromuscular activation and concentric kinetic and kinematic responses observed with CL. In addition, despite the AEL conditions involving a greater amount of work after-intervention rate of torque development and vastus lateralis contractile characteristics were not negatively impacted.

7.1.3 Chapter 4: Acute motor unit firing rate and common drive responses to lower-body single-joint AEL

In an attempt to investigate whether AEL could potentially lead to superior chronic adaptations the forth chapter of the thesis compared detailed acute neural recruitment strategy differences between the AEL and CL interventions described in Chapter 3. The acute neural responses to resistance exercise have previously been likened to motor learning with motor outputs producing greater kinematics during resistance exercise believed to be consolidated by the brain. AEL has previously been demonstrated to acutely present unique kinetic and kinematic outputs when compared to CL. In addition, heavy eccentric-only resistance exercise performed at a fast velocity has been shown to result in greater strength gains compared to equivalent training completed at a slower velocity. Therefore, in accordance with the hypotheses associating neural responses to resistance exercise to those that occur with motor learning, faster velocity AEL may be considered to lead to differential short-term neural responses that may be related to chronic adaptations. Therefore, the study had the following aims: (i) to compare vastus lateralis motor unit firing rate and common drive responses after lower-body single-joint AEL and CL; and (ii) to assess the between-test day reliability and inter-participant variability of motor unit firing rate analysis during an isometric trapezoid force trace effort.

In summary, the results of the study showed:

(i) That the firing rate of vastus lateralis later-recruited motor units was decreased following acute AEL involving a ~2 s eccentric phase, but not any of the other conditions.

(ii) That acute differences in common drive did not occur between conditions.

(iii) That the absolute and relative reliability of motor unit firing rate was greater during the plateau compared to the derecruitment and in particular the recruitment phase of the isometric knee extension trapezoid force trace effort.

The findings of the fourth chapter of the thesis indicate that single-joint lower-body AEL employing a ~2 s eccentric phase differentially effects motor unit firing rate on an acute basis compared to CL. The lack of alteration of common drive calculated from a large population of motor units following each intervention adds indirect support for existing cross-sectional and training interventions suggesting strength training may not alter common drive. Further research is required to confirm whether or not the same motor unit firing rate response occurs in a multiple-joint lower-body AEL model. In addition, further research should elucidate how acute motor unit firing rate responses change across the course of AEL training programme intervention and how AEL influences both chronic concentric and eccentric strength as a result.

7.1.4 Chapter 5: Acute neuromuscular and kinetic responses to weight releaser hook AEL back squats

Chapter 3 of the thesis investigated neuromuscular, kinetic, and kinematic responses and neuromuscular activation during knee extension AEL. However, Lower-body multiple-joint resistance exercise is considered to place greater demands on the neuromuscular and proprioceptive systems compared to single-joint resistance machine-based exercise. The neuromuscular and proprioceptive systems are likely placed under greater demands during free weight multiple-joint resistance exercise given the greater muscle mass involved, the coordination required between multiple muscles, and the need to stabilise the body in response to gravity, ground reaction forces, and momentum. Therefore, conducting a similar investigation as that detailed in Chapter 3 of the thesis was deemed necessary to assist practitioners to decide upon whether or not to employ AEL with their athletes or patients, during which training phase this type of resistance exercise variant could be implemented, and how AEL may acutely effect neuromuscular control compared to CL back squats. Determining the acute kinetic and neuromuscular activation responses to AEL back squats would inform the prescription or refinement of resistance training programmes for individuals using lower-body multiple-joint resistance exercise within athletic and rehabilitative training settings. Therefore, the aims of the study were: (i) to compare acute kinetic outputs between AEL and CL squats; (ii) to investigate how the extent of acute neuromuscular activation is effected when back squats are completed with and without weight releaser hooks; and (iii) to examine how acute activation contributions from and interaction between anterior and posterior lower-body musculature are effected during weight releaser hook AEL compared to CL squats.

In summary, the results of the study showed:

(i) That no between condition differences were observed for concentric kinetic variables or eccentric rate of force development.

(ii) That eccentric phase force was 7.0-30.0% greater in the AEL condition.

(iii) That concentric knee and hip extensor neuromuscular activation did not differ between conditions, but was elevated in the eccentric phase of AEL back squats.

(iv) That no consistent differences in neuromuscular activation contributions from knee and hip extensors were observed between conditions.

The findings of Chapter 5 suggest that weight releaser AEL squats appear to present no negative acute concentric kinetic variable responses, provide greater eccentric phase kinetic demands in terms of force production, involve greater eccentric phase knee extensor contributions across lighter and heavier loads, and do not effect the neuromuscular contributions from key agonist muscles during concentric or eccentric phases.

7.1.5 Chapter 6: Acute motor unit firing rate and common drive responses to AEL back squats

Decreases in the firing rate of later-recruited motor units were reported in the forth chapter of the thesis. However, it was unclear if the same motor unit firing rate and common drive responses observed in the single-joint resistance exercise model in used in the second and third chapters of the thesis would occur during multiple-joint

AEL. Lower-body multiple-joint resistance exercise is considered to place greater demands on the neuromuscular and proprioceptive systems compared to single-joint resistance machine-based exercise. Therefore, the aims of the study were as follows: (i) to compare vastus lateralis motor unit firing rate and common drive responses after lower-body multiple-joint free weight AEL and CL; (ii) to examine differences in lower limb maximal force production following AEL and CL; and (iii) to assess the between-test day reliability and inter-participant variability of vastus lateralis motor unit firing rates during an isometric trapezoid force trace effort, completed on a custom-built dynamometer.

In summary, the results of the study showed:

(i) That motor unit firing rate was not altered following either AEL or CL.

(ii) That an acute decrease in common drive was observed in the CL condition for maximum peak cross correlation following interventions, but mean peak cross-correlation and cross-correlation histogram distribution were unaffected.

(iii) That the absolute and relative reliability of motor unit firing rate was greater during the plateau compared to the derecruitment and in particular the recruitment phase of the isometric trapezoid force trace effort.

The findings of Chapter 6 indicated that multiple-joint lower-body AEL does not acutely influence motor unit firing rate and may only elicit minimal changes in common drive parameters. Vastus lateralis later-recruited motor unit firing rates did not decrease after the AEL intervention, as was the case following the single-joint model employed in Chapter 4. This suggests that the type of resistance exercise model used may influence acute neural responses. The lack of response in two out of three common drive measures in a large population of motor units following AEL or CL interventions, lends indirect support to suggestions from both cross-sectional and training intervention research that alterations in common drive may not occur following resistance exercise.

7.2 Contributions of the thesis to existing knowledge and thesis conclusions

The results of the studies that comprise this thesis contribute new knowledge to the AEL research literature. In particular, the way that acute motor unit recrtuitment strategy responses were investigated following AEL and CL provided a new potential approach to investigating the hypothesised similarities between motor learning and resistance exercise. Previously, only transcranial magnetic stimulation had been used for this purpose (Selvanayagam et al., 2011). The motor unit firing results observed in the third study of the thesis indicated that only AEL completed with a 2 s eccentric phase duration elicited any acute neuromuscular response. However, the contrasting motor unit firing rate and common drive response results of Chapter 4 and 6 of the thesis indicate further research is required to ascertain how acute measures quantified through the decomposition of surface EMG (such as motor unit firing rate and common drive) are related to chronic neuromuscualr adaptations following resistance exercise. A study combining acute measurements throughout the duration of a resistance training intervention study along with before- and after-intervention measures would address this question.

The findings presented in the thesis also add to the existing body of AEL research literature by providing practioners with novel data regarding the acute neuromuscular, kinetic, and kinematic responses during AEL. The results presented in Chapter 3 and 5 of the thesis suggest that AEL resistance exercise implemented in both single- and multiple-joint resistance exercise models presents no negative acute variable responses. Neither of the AEL models investigated acutely reduced concentric kinetic outputs, decreased neuromuscular contributions or activation from key agonist muscles during concentric or eccentric phases, or caused after-intervention lower-body force production or contractile characteristics to decline more than following CL. In addition, both AEL models involved greater eccentric phase lower-body extensor muscle activation compared to CL. Therefore, given these findings exercise professionals who prescribe training interventions may want to consider the use of AEL depending on the characteristics and training goals of the individuals they work with. Despite these encouraging acute neuromuscular, kinetic, and kinematic responses to AEL further research is clearly required to confirm the efficacy of AEL on a longitudinal basis. Specifically, the efficacy of AEL for the concurrent enhancement of both chronic concentric and eccentric knee and hip extensor strength, eliciting chronic neuromuscular adaptations in these muscles, and preventing injury in a range of populations remains unclear.

7.3 Thesis limitations

Finally, there were limtiations within the thesis that must be identified to in order to reduce weaknesses in future AEL and neuromuscular research. All studies within the thesis involved the measurement of lower-body force production, rate of torque development, contractile characteristics, motor unit firing rate, or common drive at only a single acute time-point following the single- and multiple-joint AEL models that were investigated. Previously, transcranial magnetic stimulation research has demonstrated particular time-course responses for twitch force magnitude and direction following acute bouts of different types of resistance exercise. These distinct transcranial magnetic stimulation responses have been shown to last for at least 25 min following resistance exercise (Selvanayagam et al., 2011). Due to the number of different measurements performed following each AEL and CL intervention, the time required to perform each measurement, and the need to provide participants with recovery between assessments it was not feasible to perform multiple measurements in the time immediately following each intervention. However, measurements could have been performed beyond the time immediately following the AEL intervention to ascertain the time course before variables returned to baseline. In particular, time-points corresponding to typical time periods between training sessions for athletes completing concurrent training could have been used to enhance the practical application of the results. In addition, measuring involuntary muscle responses at the same time-point as motor unit firing rate and common drive would have provided a definite indication that there were no local muscular changes that could have influenced motor unit firing rate or common drive measurements.

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APPENDICES

Appendix A: Example participant information sheet

PARTICIPANT INFORMATION SHEET

Reliability of Reporting Muscle Activity during Free Weight Squatting as a Percentage of Voluntary Maximal and Submaximal Contraction Protocols.

Primary Investigator:
Tom Balshaw. Postgraduate Research Student, University of Stirling. (email: t.g.balshaw@stir.ac.uk, mobile: 07703055187)

Investigation Supervisor:
Dr Angus Hunter. Lecturer, University of Stirling (email: a.m.hunter1@stir.ac.uk)

You are invited to take part in the above titled sports science research project. To ensure you are fully aware of why you have been asked to participate and the activity involved (should you choose to participate), it is important to provide you with some more details. Please read the following information carefully and discuss it with those who may be required, or you feel will help you make a decision on whether or not to participate in the study. If you have any questions regarding any aspect of the study please contact either the researcher or research supervisors via their contact details (listed above).

Purpose of the study.

i) The primary purpose of the study is to determine the most reliable way of reporting muscle activity at different loading levels during the dynamic resistance training exercise, the free weight back squat.

ii) The secondary purpose of the project is to investigate the relationship between the level of muscle activation and the percentage of relative back squat load (e.g. percentage of one repetition maximum for each individual participant).

The findings of this study will provide a strong rationale for the use of one of three methods of reporting muscle activity in a subsequent research project and will also allow evaluation of the relationship between back squat intensity and muscle activation to determine the response of muscle activity to a range of back squat loads.

Why we would like you to participate.

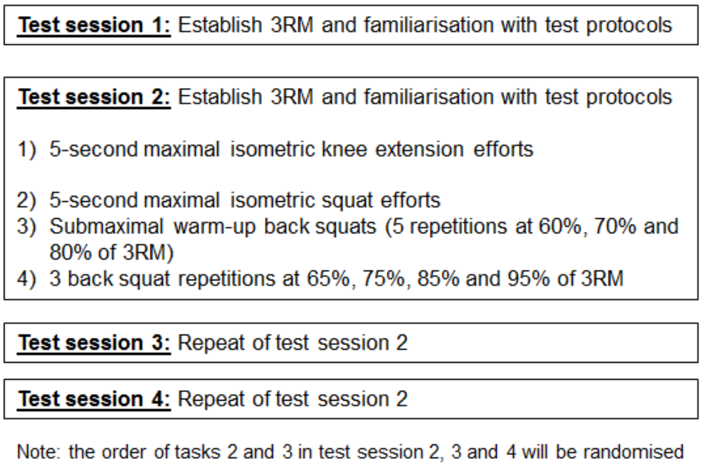
You have been selected because you are a resistance trained habitual squatter (with a resistance training age of at least 2 years). The study subsequent to this investigation will investigate immediate responses to an advanced type of strength training that resistance trained individuals may use, therefore in the current study it is important to use individuals of similar resistance training age to ensure measures taken can be consistently reproduced and are representative of the desired dependent variables.

Do you have to take part?

This sheet is simply an invitation to take part in the study, once you have thoroughly read the information provided it is your own decision whether or not you wish to take part in the project. If you decide to take part you will be asked to sign a sheet confirming your informed consent. Signing the informed consent does not mean you have to finish the project testing and you will be free to withdraw your consent at any point during the project without giving reason, if you decide to withdraw from the project you will still receive the same high level of treatment.

What are you required to do if you participant in this study?

Individuals recruited for testing will be required to take complete rest or only undertake very easy exercise and also maintain their usual dietary habits and record a food diary (intake to be reproduced before subsequent sessions) in the 24 hours before testing sessions. Participating in this study will involve visiting the University four times for testing sessions (one per week) over a 4 week period. The first session will last approximately one hour and will involve the establishment of 3 RM back squat performance and familiarisation with the maximum contraction procedures used in the following sessions. Testing session 2, 3 and 4 will last approximately one hour, with the first 20 minutes involving preparation of the participant’s skin (shaving of hair on the two lower limb muscle sites required to be measured, alcohol swabbing and skin abrasion of these sites) and placement of sensors to measure muscle activity (1 quadriceps muscle and 1 hamstring muscle). Following the application of muscle sensors participants will complete two maximal contraction and one sub-maximum contraction protocols. Subsequent to these three tasks, four incremental intensity sets of three repetitions of back squats will be completed (Figure 1 lists back squat intensities) with muscle activity measured during all activities. The loads prescribed will equate for differences in body mass so all individuals are lifting the same relative intensity (e.g. System Mass 3 RM= body mass plus weight lifted during 3 RM testing, values below are percentage of system mass 3 RM).



Test session 1: Establish 3RM and familiarisation with test protocols

Test session 2: Establish 3RM and familiarisation with test protocols

1) 5-second maximal isometric knee extension efforts
2) 5-second maximal isometric squat efforts
3) Submaximal warm-up back squats (5 repetitions at 60%, 70% and 80% of 3RM)
4) 3 back squat repetitions at 65%, 75%, 85% and 95% of 3RM

Test session 3: Repeat of test session 2

Test session 4: Repeat of test session 2

Note: the order of tasks 2 and 3 in test session 2, 3 and 4 will be randomised

Figure 1. Test Protocol.

Risks and benefits of participation.

When participating in maximal lifting efforts there is always a chance that muscle injury can occur, individuals will undergo the familiarisation session and on the day of testing a thorough warm up. Session 1 (familiarisation) will allow individuals who have never completed maximal isometric contractions of the knee extensor muscles on the isokinetic dynamometer and maximal isometric squats the opportunity to become used to these procedures prior to session 2, 3 and 4. Appropriate spotting procedures will be implemented for all trials. As resistance trained habitual squatters participants will not be exposed to any risks or loads they are not facing regularly in training in sessions 2, 3 and 4.

The main benefit for participants will be the provision of their body composition and 3 RM back squat assessment results. The role recruited individuals will play in establishing reliable methods may also be beneficial to their longer term sporting performance as the research group conduct further work investigating advanced strength training methods, with the option for the findings of subsequent projects to be provided to the individuals and/or their coaches.

Confidentiality.

Your identity will be kept confidential and any information will be stored under the restrictions outlined in the data protection act (1998). At the commencement of the study, you will be allocated a participant code, which will be the only means of identifying your results. Under no circumstance will your name appear in any publication arising from this study.

Results.

The results of the study will be made available to you and/or your coach as a concise summary (if you wish) and will be published in a scientific peer reviewed journal at some point after 2010. None of the participant’s identities as stated in the confidentiality section (above) will be included in any publication.

Ethical approval.

This study has been reviewed and approved by the University of Stirling Research Ethics Committee.

Contact for further information.

If you have any questions or concerns please feel free to contact the primary investigator and or investigation supervisors (contact information is listed at the top of this information sheet).

Please note you will be issued with a copy of this information sheet and the informed consent sheet should you decide to participate in the study.

Appendix B: Example informed consent sheet

INFORMED CONSENT FORM

CONSENT BY PATIENT/VOLUNTEER TO PARTICIPATE IN: A sports science research project at the University of Stirling

Name of Patient/Volunteer: ....

Name of Study: Reliability of reporting muscle activity during free weight squatting as a percentage of voluntary maximal and sub-maximal contraction protocols

Principal Investigator: Tom Balshaw

I have read the patient/volunteer information sheet on the above study and have had the opportunity to discuss the details with the principal investigator and/or the research supervisors and ask questions. The principal investigator has explained to me the nature and purpose of the tests to be undertaken. I understand fully what is proposed to be done.

I have agreed to take part in the study as it has been outlined to me, but I understand that I am completely free to withdraw from the study or any part of the study at any time I wish. I understand and agree that my participation in the study is entirely at my own risk.

I understand that these trials are part of a research project designed to promote scientific knowledge, which has been approved by the Sports Studies Ethics Committee, and may be of no benefit to me personally. The Sports Studies Ethics Committee may wish to inspect the data collected at any time as part of its monitoring activities.

I also understand that my General Practitioner may be informed that I have taken part in this study if any unusual or surprising observations are made (If I agree for contact to be made).

I hereby fully and freely consent to participate in the study which has been fully explained to me.

Signature of Participant: ....

Date: ....

I confirm that I have explained to the patient/volunteer named above, the nature and purpose of the tests to be undertaken.

Signature of Investigator: ....

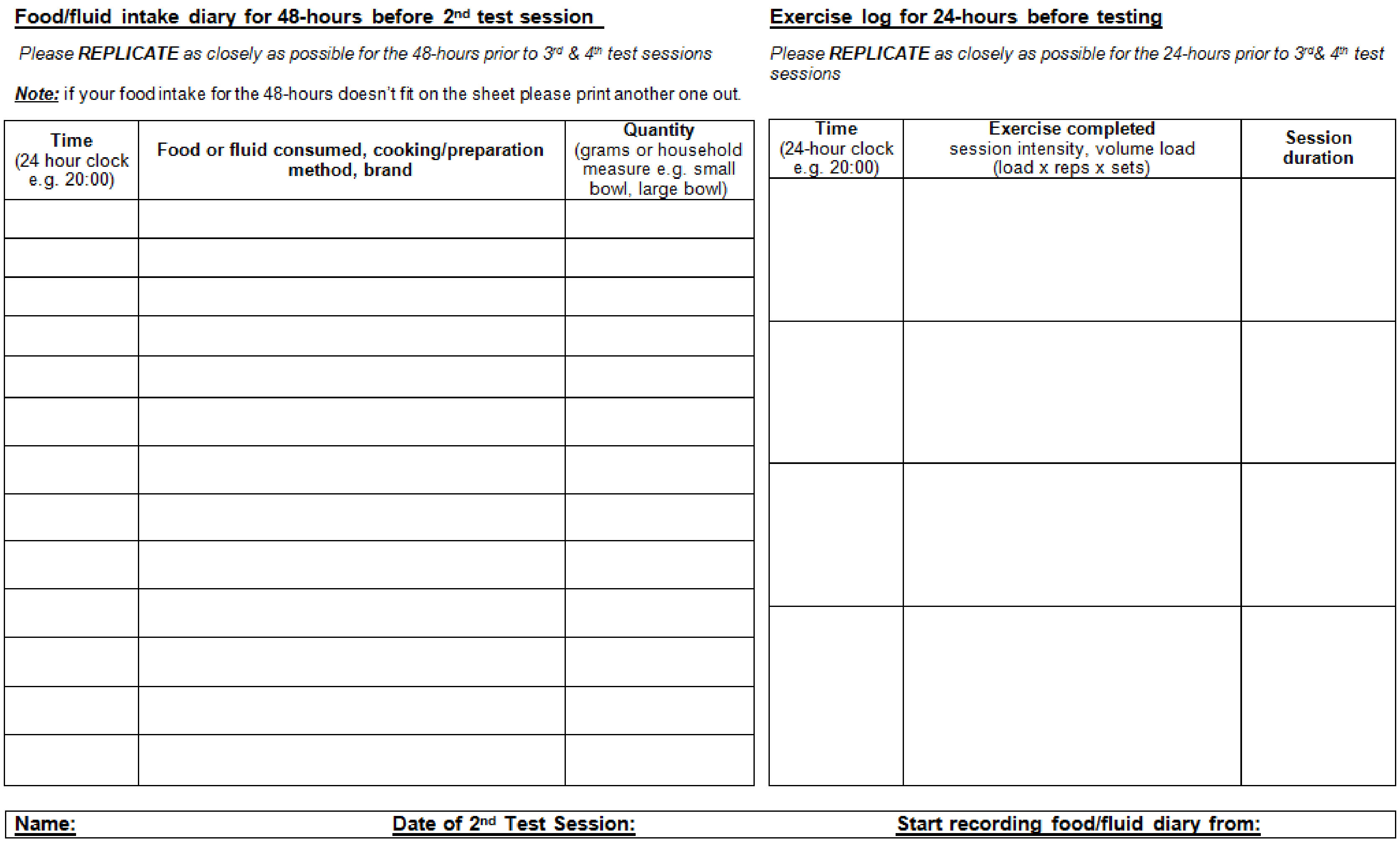
Date: ....

Appendix C: Example body composition assessment sheet

BODY COMPOSITION ASSESSMENT SHEET

Participant Code				
Participant Name				
Sex (male=1, female=2)				
Sport				
Date of Measurement				
Date of Birth				
Measure	***1***	***2***	***3***	***3rd Measure?***
Body mass				
Stretch stature				
Triceps sf				
Subscapular sf				
Biceps sf				
Iliac Crest sf				
Supraspinale sf				
Abdominal sf				
Front Thigh sf				
Medial Calf sf				

Appendix D: Example food and fluid intake diary/exercise log



Food/fluid intake diary for 48-hours before 2nd test session

*Please **REPLICATE** as closely as possible for the 48-hours prior to 3rd & 4th test sessions*

Note: if your food intake for the 48-hours doesn't fit on the sheet please print another one out.

Time (24 hour clock e.g. 20:00)	**Food or fluid consumed, cooking/preparation method, brand**	**Quantity** (grams or household measure e.g. small bowl, large bowl)

Exercise log for 24-hours before testing

*Please **REPLICATE** as closely as possible for the 24-hours prior to 3rd & 4th test sessions*

Time (24-hour clock e.g. 20:00)	**Exercise completed** session intensity, volume load (load x reps x sets)	**Session duration**

Name: **Date of 2nd Test Session:** **Start recording food/fluid diary from:**

Appendix E: Motor unit firing rate analysis information

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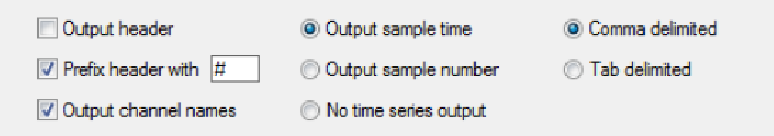
02215, U.S.A.

Detailed Module Specifications

This function is designed to be used on firing data generated by PDsEMG and extracted using the "Firings" button *without* "stagger output.." selected. The firing data should then be exported to CSV from the Tools menu in EMGworks with the following options selected:



☐ Output header
☑ Prefix header with #
☑ Output channel names

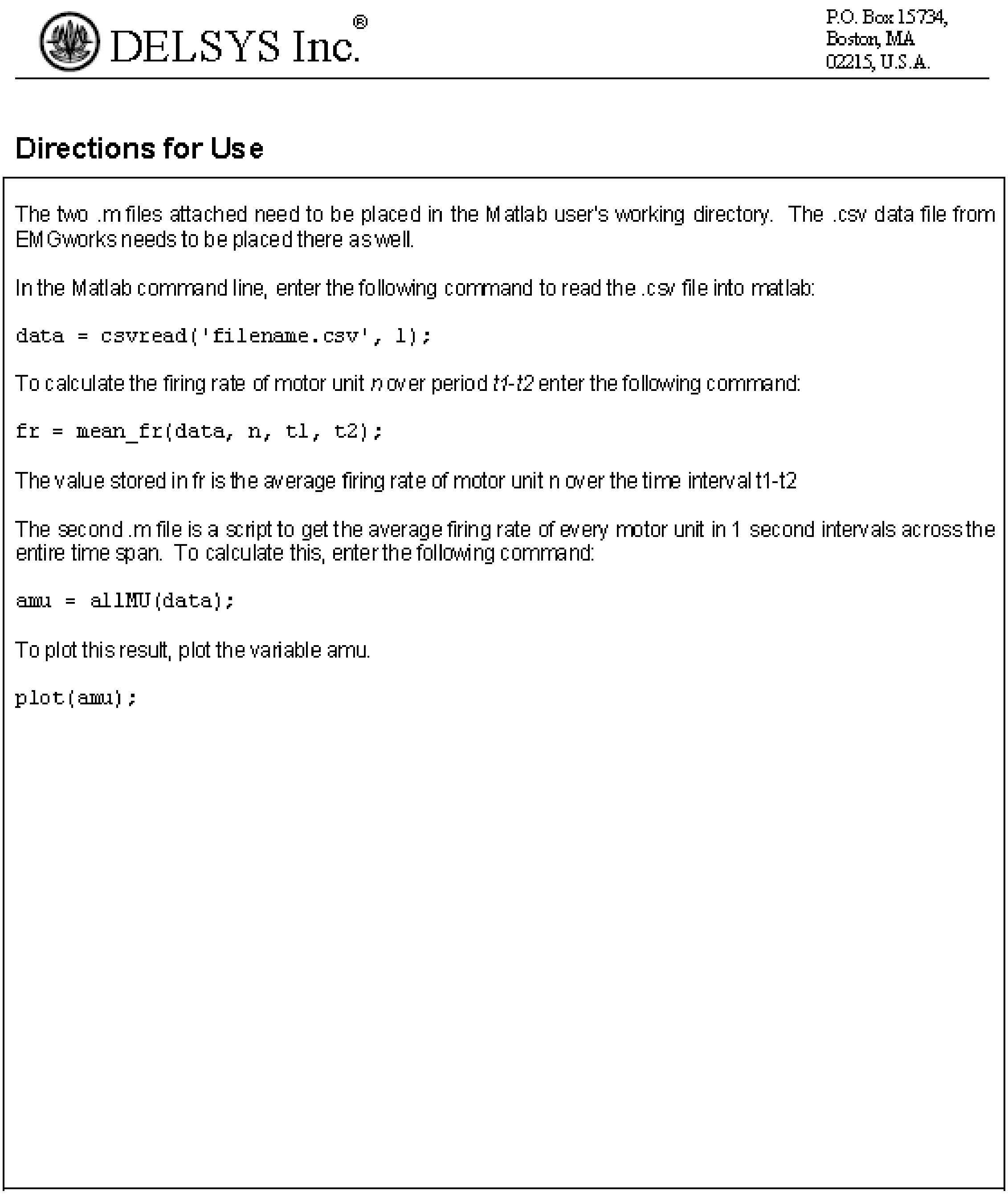
● Output sample time
○ Output sample number
○ No time series output

● Comma delimited
○ Tab delimited

This function returns one variable: the average firing rate of a specified motor unit over a specified period of time. It is called as such:

```
fr = mean_fr(data, n, t1, t2);

Variable descriptions:
fr = calculated average firing rate
data = exported EMGworks data, read into matlab
n = motor unit number
t1 = start time
t2 = end time
```



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Directions for Use

The two .m files attached need to be placed in the Matlab user's working directory. The .csv data file from EMGworks needs to be placed there as well.

In the Matlab command line, enter the following command to read the .csv file into matlab:

```
data = csvread('filename.csv', 1);
```

To calculate the firing rate of motor unit *n* over period *t1-t2* enter the following command:

```
fr = mean_fr(data, n, t1, t2);
```

The value stored in fr is the average firing rate of motor unit n over the time interval t1-t2

The second .m file is a script to get the average firing rate of every motor unit in 1 second intervals across the entire time span. To calculate this, enter the following command:

```
amu = allMU(data);
```

To plot this result, plot the variable amu.

```
plot(amu);
```

Appendix F: Common Drive analysis information

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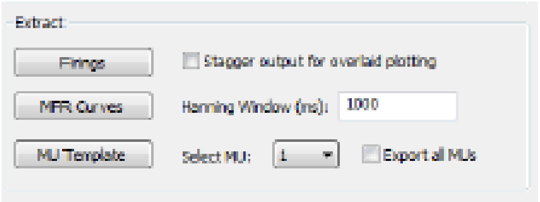
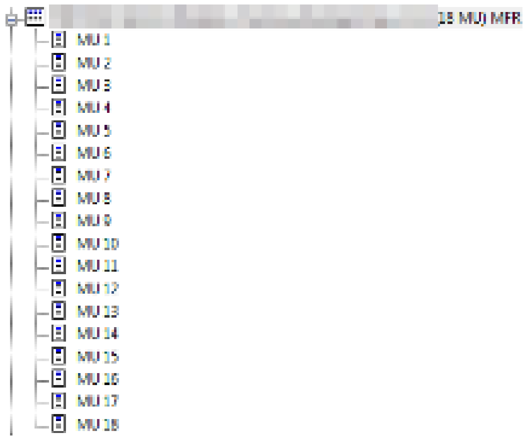
Detailed Module Specifications

This function is designed to be used on mean firing rate data generated by dEMG and extracted using the "MFR Curves" button. The suggested Hanning window width to be used for this analysis is 800 ms, but values in the range of 400 to 1600 ms are acceptable.



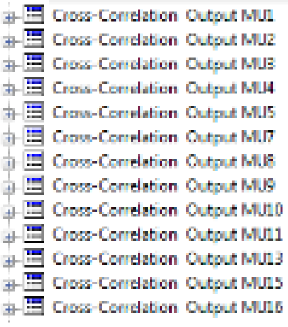
☐ Stagger output for overlaid plotting
Hanning Window (ms): 1000
Select MU: 1
☐ Export all MUs

The output of this calculation must be then input in pairs into the script to obtain correlations for all possible combinations of motor units.



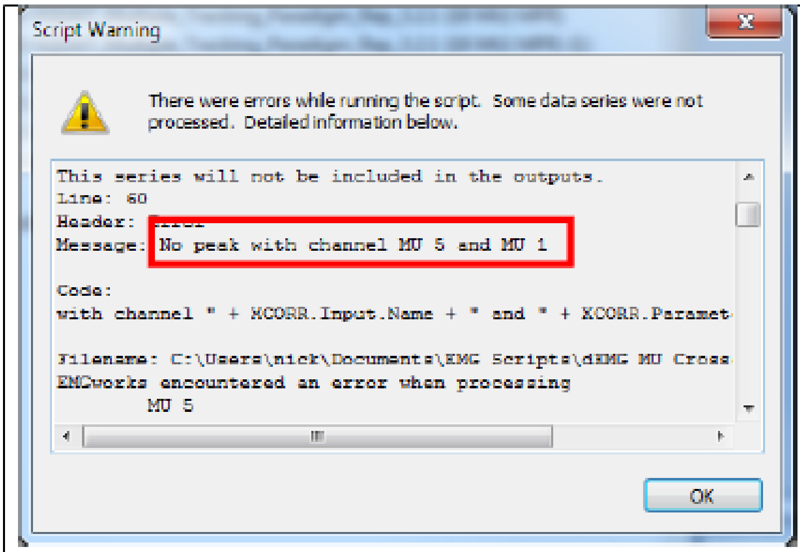
[redacted]18 MU) MFR
MU 1
MU 2
MU 3
MU 4
MU 5
MU 6
MU 7
MU 8
MU 9
MU 10
MU 11
MU 12
MU 13
MU 14
MU 15
MU 16
MU 17
MU 18

The most expedient way to do this, assuming *n* motor units are decomposed is to Ctrl-Select MU2 through MU #*n*. Then choose the "Correlate with" series as MU1. Next, Ctrl-select MU3 through MU #*n*. For this group the "Correlate with" series is MU 2. Continue this process until only MU #*n* is selected and the "Correlate with" series is MU #(*n*-1). This will generate outputs for all series which have correlations in the peak search interval. The outputs may be named appropriately for easy inspection, as seen below.



Cross-Correlation Output MU1
Cross-Correlation Output MU2
Cross-Correlation Output MU3
Cross-Correlation Output MU4
Cross-Correlation Output MU5
Cross-Correlation Output MU7
Cross-Correlation Output MU8
Cross-Correlation Output MU9
Cross-Correlation Output MU10
Cross-Correlation Output MU11
Cross-Correlation Output MU13
Cross-Correlation Output MU15
Cross-Correlation Output MU16

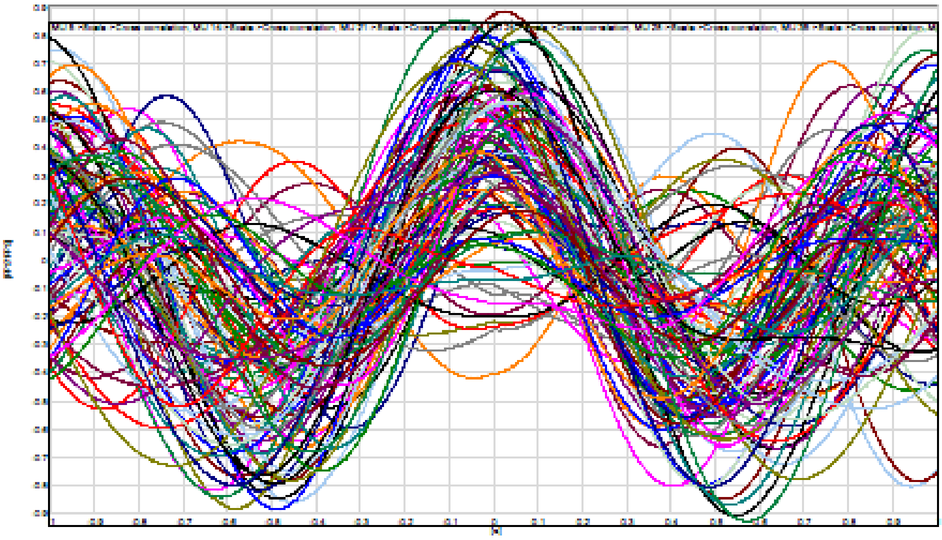
Not every MU pair will exhibit strong correlation within the specified interval. For those series that do not, the script will output an error message, as seen below. This allows only those pairs which have correlation in the specified interval to be studied easily, with no extraneous outputs.



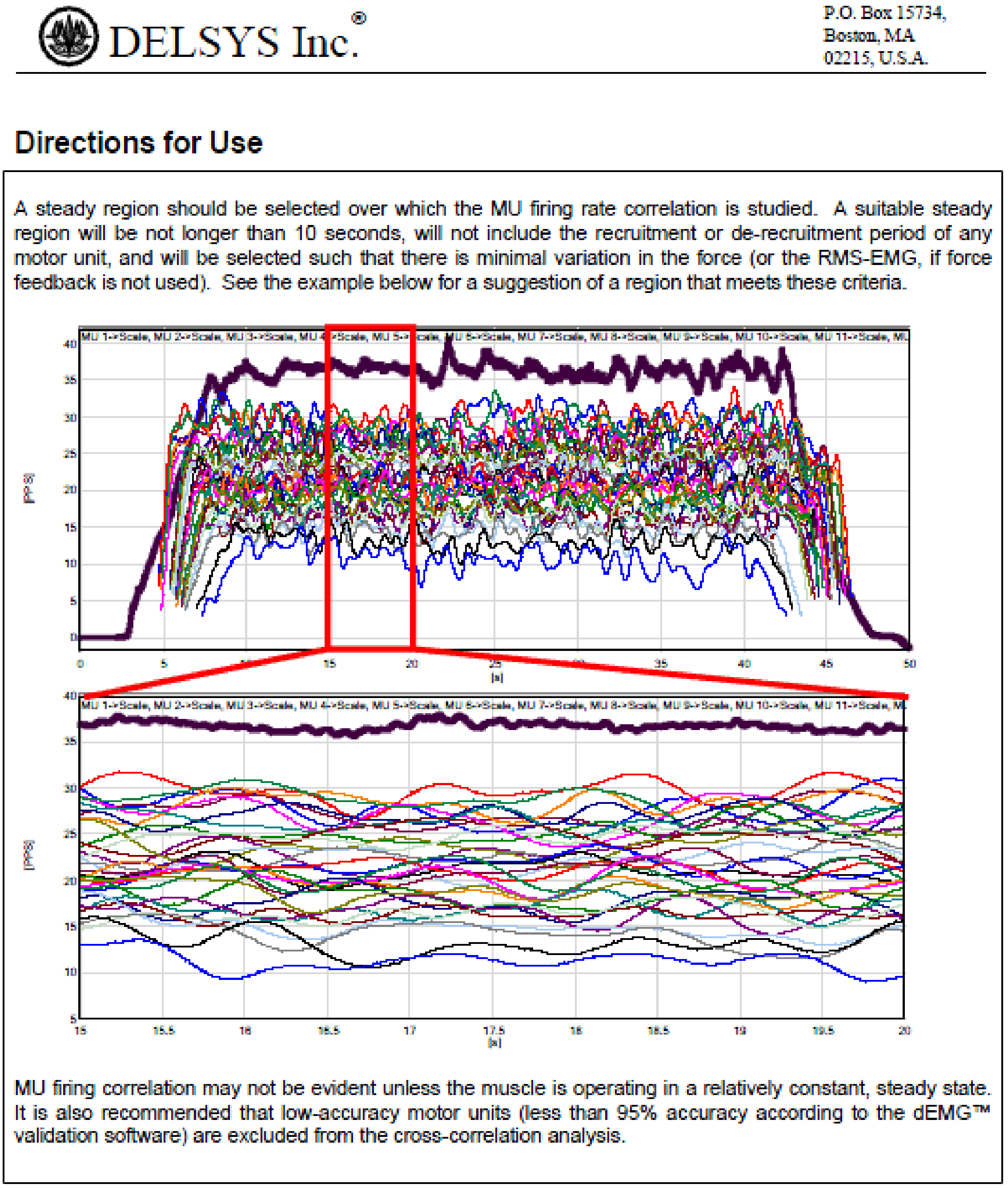
There were errors while running the script. Some data series were not processed. Detailed information below.

```
This series will not be included in the outputs.
Line: 60
Header: [illegible]
Message: No peak with channel MU 5 and MU 1

Code:
with channel " + XCORR.Input.Name + " and " + XCORR.Paramet

Filename: C:\Users\nick\Documents\EMG Scripts\dEMG MU Cross
EMGworks encountered an error when processing
        MU 5
```

An overlaid plot will display all correlation curves that show a peak, as below.



By exporting the data to Excel, histograms of the time-lag and peak correlation values can be created.



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Directions for Use

A steady region should be selected over which the MU firing rate correlation is studied. A suitable steady region will be not longer than 10 seconds, will not include the recruitment or de-recruitment period of any motor unit, and will be selected such that there is minimal variation in the force (or the RMS-EMG, if force feedback is not used). See the example below for a suggestion of a region that meets these criteria.

MU firing correlation may not be evident unless the muscle is operating in a relatively constant, steady state. It is also recommended that low-accuracy motor units (less than 95% accuracy according to the dEMG™ validation software) are excluded from the cross-correlation analysis.