Investigations of the Neuromuscular Response During and Following Elite Maximum Strength and Power Type Resistance Exercise

By Raphael Brandon.

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Abstract

The thesis aimed to analyse the acute neuromuscular (NM) response during and following maximum strength and power training methods.

The primary aim of study one was to establish the reliability of biomechanical and surface electromyographic (sEMG) measurements during barbell squat exercise. This would enable the subsequent studies to precisely assess muscle activity and mechanical power during barbell resistance exercise sessions. Nine male well-trained subjects performed squat exercise on three separate trial days. Each trial comprised one set of squat at 50, 75 and 100% of 3RM load. Synchronous recordings of knee joint kinematics from a flexible electrogoniometer, barbell displacement from a single linear position transducer and quadriceps sEMG amplitude were made. The mean maximum knee angle during squat was recorded at each load, and the overall inter-trial coefficient of variation (CV) was 5.5%. Mean concentric repetition power was processed from displacement data and derived into force and velocity values. The overall inter-trial CV for mean power was found to be 8.4%. The raw sEMG signal was processed into root mean square (RMS) amplitude and normalised to values taken from pre-trial knee extension maximum voluntary contractions (MVC). RMS amplitude was processed for the whole concentric phase and a 200 ms time interval at a knee angle of 70°, which matched the knee angle used during MVC. Inter-trial CV for RMS amplitude from the concentric phase and 70° knee angle were 7.2% and 16.4% respectively. There were no differences in RMS amplitude, maximum knee angle or mean power across trial days. It was concluded there was acceptable reliability for all three measurements (CV < 10%), if RMS amplitude was processed from the concentric phase. Based upon the measurement reliability, the analysis system was considered suitable for monitoring power and sEMG during barbell exercise.

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The second study aimed to establish the reliability of muscle fibre conduction velocity (MFCV) measurements during barbell squat. This was of interest, as MFCV may provide useful information of NM recruitment and fatigue processes during resistance exercise. The study was also used as a preliminary investigation of MFCV response, in comparison to RMS amplitude, to increasing fatigue and load during squat exercise. Nine well-trained male subjects performed a series of exercises on two separate trial days. Each trial comprised isometric knee extensions at 50, 75 and 100% of MVC force, followed by barbell squats at 50, 75 and 100% of 3RM, and then a maximal bout of squat jumps at 50% 3RM load, performed until failure. sEMG measurements were recorded from a four-electrode array, secured upon the *vastus lateralis*. Normalised RMS amplitude was processed as above, and MFCV was processed from the inter-electrode distance and time delay between two double differentiated and correlated signals, using bespoke software. The overall value of MFCV during squat was 5.8 $m.s^{-1}$. The inter-trial CV for MFCV was 9.6% during squat and 12.1% during squat jump. Based upon acceptable reliability of 10%, MFCV measurements from barbell squats were considered reliable. As expected, MFCV significantly increased with each knee extension force level (4.7 ± 1.4, 5.6 ± 1.5 and 6.2 ± 1.8 $m.s^{-1}$) ($p<0.01$), along with RMS amplitude ($p<0.0001$). No differences in MFCV were found between squat loads, whilst RMS amplitude significantly increased with load ($p<0.0001$). Power (1920 ± 143 versus 1407 ± 254 W) and MFCV (5.7 ± 1.4 versus 4.6 ± 1.0 $m.^{s-1}$) significant decreased ($p<0.001$) from the start to the end of the squat jump trial, with RMS amplitude unchanged. Therefore, MFCV altered with increasing fatigue, but not load, during dynamic squat exercise. It was concluded that MFCV provides useful and reliable data for acute fatigue investigations of barbell resistance exercise, in addition to sEMG amplitude measures.

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The following three investigations compared NM responses during and following maximum strength and power type resistance exercise sessions with different exercises, loads and movement speeds. The sessions were designed to represent elite athlete training practices, to help inform the optimisation of resistance exercise programmes. The first of these studies aimed to compare NM response to a typical maximum strength session performed with barbell squat or deadlift exercise. The purpose was to assess if technical differences between the exercises, influenced the acute NM response. Nine elite trained weightlifters performed the trial sessions of five sets of five repetitions on separate days. Normalised RMS amplitude, MFCV and power was continually measured during exercise repetitions, using the methods established above. NM function was assessed pre- and post-sessions using MVC force, central activation ratio (CAR) from superimposed stimulation during MVC, and jump performance (CMJ). The exercises were performed with subjectively matched load levels, corresponding to active muscle RPE = 17 (Borg scale), and also with controlled lifting speed. However, the squat load was lowered and raised upon the lifter's back, whilst deadlift load was grasped in the hands, raised from the floor and then dropped. Repetition mean power was unchanged within and across sets of both sessions. Repetition RMS amplitude significantly increased ($p<0.001$) within sets of squat and deadlift, whilst a significant interaction between sessions and set ($p<0.001$) demonstrated RMS increased more during squat. Furthermore, a significant reduction in repetition MFCV was found within sets of squat ($p = 0.034$), but not deadlift. This suggests that motor unit activation increased during both exercises, as a response to the task of maintaining power during repetitions of whole body lifting. However, acute fatigue within squat sets led to additional increased activation as a NM compensation strategy. No pre- versus post- session differences were found for MVC, CAR or CMJ; suggesting minimal change in NM function occurred following five sets of maximum strength type resistance exercise, in well-trained subjects.

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The primary aim of the second study was to compare NM response and 24-hour recovery following barbell exercise maximum strength and power type sessions. The purpose was to specifically establish the degree and nature of NM response, as previous findings were unclear and barbell exercise sessions of this type have not been compared. 10 elite sprint athletes performed sessions comprising squat, split squat and push press, with four sets x repetitions per exercise. The maximum strength session exercises involved loads corresponding to active muscle RPE = 17 (Borg scale) and metronome controlled movements. The power session exercises used 30% of the maximum strength barbell load, performed as fast as possible. Repetition sEMG and power was monitored throughout each session, as above. NM function was assessed, pre-, post- and 24-hour post- each session, using the same tests as above. However, evoked peak twitch force (Pt) was also included to the pre- and post- assessments. Overall, the maximum strength session involved greater total work ($p = 0.008$), but lower mean power during exercise repetitions ($p<0.001$) in comparison to the power session. MVC and Pt force values both significantly decreased ($p<0.05$) pre- versus post- both sessions. However, MVC reduced more following maximum strength session ($p<0.01$). CAR and CMJ were unchanged post- both sessions and no differences were found between pre and 24-hour post session NM tests. The decreased Pt but not CAR findings, suggest peripheral fatigue explains the reduced force generation capacity following maximum strength and power sessions, contrary to previous resistance exercise session findings. Up to 24-hours may be required to recover force generation capacity following this volume of resistance exercise. Additional analysis suggested strength levels influenced the degree of fatigue following the power session. This was because barbell exercises involve lifting body mass and bar mass. Therefore, stronger subjects lifted relatively lighter loads during a barbell power session using 30% of bar mass. This supports the use of system mass loads to determine relative load levels during power type sessions.

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The aim of the final study was to compare NM and hormonal response following high intensity 'explosive' squat at three load levels. This training method is specific to elite athletes and has not been previously assessed. The purpose was to further understanding of the load level of explosive exercise that provides the most effective training stimulus. 15 elite power athletes, from track and field and rugby, completed 10 sets of high intensity squat exercise on three separate days. The heavy session involved loads corresponding to active muscle RPE = 17 (Borg scale), as above. The moderate and light sessions were 75% and 50% system mass of heavy session load, respectively. The execution of every repetition was maximal in all three sessions. Methods followed previous studies with the addition of isometric knee extension rate of force development (RFD) and loaded squat jump (SJ) power to the NM function tests. Saliva samples were taken at baseline, mid-, and post- session for testosterone (T) and cortisol (C) assay analysis. Heavy session involved greatest repetition impulse in comparison to moderate and light sessions ($p<0.001$), whilst light session involved highest repetition power ($p<0.001$). Total work performed in each session was similar. MVC, RFD and Pt force values were significantly reduced post- sessions ($p<0.01$). However, MVC and RFD reduced most following heavy, then moderate and then light sessions. This corresponded to significantly reduced repetition power during sets of the heavy session only ($p<0.001$). Repetition RMS amplitude also increased most during sets of heavy session ($p<0.001$), followed by moderate, with no change during light session. These findings suggest NM response was greatest during heavy session, providing effective training stimulus, but so was acute NM fatigue. Moderate load explosive exercise may also provide sufficient NM stimulus, however with less fatigue. Decrement in RFD was significantly greater than MVC force ($p<0.001$), and was reduced mid- as well as post- session. This suggests high intensity squat training affects NM mechanisms related to RFD capacity. No significant changes in CAR, CMJ or loaded SJ were found. Significant reductions in C relative to baseline

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($p<0.001$) occurred mid- and post all three sessions, as expected following circadian rhythms. A significant interaction between session and time ($p<0.01$) was found, where T was maintained relative to baseline following moderate and heavy sessions, but reduced following the light session. This also suggests heavy and moderate high intensity sessions may provide more effective training stimulus than light load.

The findings of this thesis show that the NM response during maximum strength and power type resistance exercise sessions involves increased motor unit activation within exercise sets. This may occur without fatigue during exercise repetitions and indicates the NM stimulus for adaptation. The nature of NM fatigue following maximum strength and power training, in terms of reduced force generation, involves peripheral, and not central, mechanisms, contrary to previous conclusions and general belief amongst sports coaches. Importantly, stimulus may not be directly related to the degree of post-session NM fatigue, but instead the NM activation during exercise repetitions. The data implies certain exercises (e.g. deadlift and explosive moderate load squats) provide sufficient stimulus for adaptation, with a limited NM fatigue response. This informs training programme design for elite athletes completing diverse and concurrent training activities.

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List of Figures and Tables

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Glossary of terms

BF	*Biceps femoris* muscle
C	Cortisol
CAR	Central Activation Ratio assessment
CMJ	Counter movement jump or Vertical jump
CV	Coefficient of variation
E-C coupling	Excitation-contraction coupling
ICC	Intra-class coefficient of correlation
NM	Neuromuscular
NMJ	Neuromuscular junction
MFCV	Muscle fibre conduction velocity
MVC	Maximal voluntary contraction force assessment
Pt	Peak evoked twitch force
RFD	Rate of force development
RTD	Rate of twitch development defined by dF/dt during Pt
RM	Repetition maximum
RMS	Root mean square
sEMG	Surface electromyography
SJ	Squat jump
SM	System mass
T	Testosterone
T:C	Testosterone to cortisol ratio
Tf:Tc	Flight time to contraction time ratio during CMJ
TUT	Time under tension
VA%	Voluntary activation assessment
VL	*Vastus lateralis* muscle

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Introduction

Athletes perform resistance exercise to improve functional movement and sports performance (Haff *et al.*, 1997; Mero & Komi, 1994; R. U. Newton, Kraemer, & Hakkinen, 1999; Saunders *et al.*, 2006; Stone et al., 2003; Wilson, Newton, Murphy, & Humphries, 1993). Specific types of resistance exercise are chosen to develop different physical qualities. Sessions comprising high intensity (above 80% of maximum load) and low repetitions (two to six) are used to develop maximum strength, whilst moderate loads (50-80%) and higher repetitions (six to 12) are used to develop muscle size, known as hypertrophy (ASCM, 2009; Crewther, Cronin, & Keogh, 2005). Sessions comprising relatively low load, but performed with high velocity are used to develop power (McBride, Triplett-McBride, Davie, & Newton, 2002; Moss, Refsnes, Abildgaard, Nicolaysen, & Jensen, 1997; Wilson *et al.*, 1993).

The chronic responses to maximum strength (Kramer *et al.*, 1997) and power (Cormie, McGuigan, & Newton, 2010b) training are widely researched and have led to established training principles (Stone, Collins, Plisk, Haff, & Stone, 2000). Specifically, maximum strength type training increases neural activation of the motor units and cross sectional area of the muscles fibres (Aagaard, 2003; Campos *et al.*, 2002; Fry, 2004; Sale, 1988; Schoenfeld, 2010). Consequently, training for maximum strength forms an important part of an athlete's programme, due to the potential for increased force development (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002a). Power type training also enhances neural drive, particularly rapid motor unit activation (Van Cutsem, Duchateau, & Hainaut, 1998) and is related to improved athletic performance (Wilson *et al.*, 1993). Therefore, the chronic adaptations to resistance exercise are beneficial for athletes, and involve both peripheral (muscle fibre hypertrophy) and central (motor unit activation) mechanisms of the neuromuscular (NM) system.

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However, the acute training session responses that optimise chronic adaptation are not directly known and specific investigations are required to further understanding (McCaulley *et al.*, 2009). This is of interest, as specific responses may enhance the effectiveness of the resistance exercise sessions, leading to increased chronic adaptation. For example, recruitment of a high proportion of type II motor units during training is important (Behm, 1995), and has been associated with enhanced cross sectional area and force adaptations (Takarada, Takazawa, *et al.*, 2000). In addition, metabolite accumulation and changes in contractile function may indicate the necessary stimulus for protein muscle synthesis following resistance exercise (Holm *et al.*, 2008). Therefore, further knowledge of the acute NM response to maximum strength and power type sessions may help optimise the planning and execution of resistance exercise.

Surface electromyography (sEMG) measures have been used to investigate NM recruitment relating to and influencing force generation during exercise (De Luca, 1997; Potvin & Bent, 1997). Specific responses are found during isometric maximal and submaximal contractions (Arendt-Nielsen, Mills, & Forster, 1989; Moritani, Muro, & Nagata, 1986) and dynamic single joint tasks, such as knee extensions (Hassani *et al.*, 2006; Pincivero, Gandhi, Timmons, & Coelho, 2006). Previous sEMG research typically assesses single exercise bouts to fatigue, as clear changes in sEMG are observable. Fatigue is defined as a progressive reduction in the force or power generating capacity as a result of exercise (Cairns, Knicker, Thompson, & Sjogaard, 2005; Enoka & Duchateau, 2008; Gandevia, 2001). However, few studies have analysed structured sessions of resistance exercise comprising sets of repetitions, separated by rest intervals (Smilios, Hakkinen, & Tokmakidis, 2010). No studies have specifically investigated sEMG during maximum strength and power type sessions, as defined above, and so the NM response that may indicate a stimulus for adaptation is unknown.

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NM fatigue has also been investigated using voluntary maximal force assessment following sustained isometric force tasks or single bouts of dynamic exercise. This is commonly combined with evoked twitch assessment, as a measure of contractile function (Fowles & Green, 2003), along with a measure of motor unit activation, such as stimulated superimposed force (Kent-Braun, 1999). This research has shown that NM fatigue varies as a result of exercise intensity (Yoon, Schlinder Delap, Griffith, & Hunter, 2007), duration (Behm & St-Pierre, 1997; Sogaard, Gandevia, Todd, Petersen, & Taylor, 2006) and type of contraction (Babault, Desbrosses, Fabre, Michaut, & Pousson, 2006). For example, Klass, Guissard, & Duchateau (2004) used these methods to identify specific peripheral mechanisms that explain the reduced force generation capacity following a bout of repetitive, dynamic contractions. Few studies have applied this methodological approach to investigate NM fatigue following whole, structured sessions of resistance exercise.

Previous investigations have assessed NM fatigue following high intensity (Hakkinen, 1993), high volume (Hakkinen, 1994), and high velocity (Linnamo, Hakkinen, & Komi, 1998) resistance exercise sessions, using force, sEMG and lactate measurements. These studies concluded that both peripheral and central mechanisms contributed to reduced force generation capacity. However, this was based upon indirect measures. In particular, sEMG may not solely represent central mechanisms, as peripheral fatigue processes could alter the sEMG measurement, independent of neural drive (Perrey, Racinais, Saimouaa, & Girard, 2010). In contrast, different investigations found no evidence of reduced central activation following resistance exercise based upon findings from force, evoked twitch and superimposed force assessments (Behm, Reardon, Fitzgerald, & Drinkwater, 2002; Tran, Docherty, & Behm, 2006). Therefore, the understanding of NM fatigue following maximum strength and power sessions is unclear, due to different methodologies used. Specific investigations of the NM response of entire resistance exercise sessions

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comprising different intensity, volume and contraction velocity would be of interest. For example, elite athletes perform 'explosive' resistance exercise with a range of loads, to promote the neuromuscular adaptation process (Behm, 1995; Behm & Sale, 1993a). However, these sessions have rarely been investigated.

From this brief introduction it is clear that gaps in the current knowledge exist. Firstly, the sEMG response that may indicate NM recruitment strategies specifically during maximum strength and power type exercise has not been established. Secondly, the acute NM response following resistance exercise sessions that comprise high loads, high velocity or a combination of the two, warrants further investigation. As stated, this is of interest for understanding adaptation processes. In addition, greater knowledge of the acute NM response may inform training planning. For example, the degree of fatigue resulting from the session directly influences the recovery time. Furthermore, the nature of fatigue may influence the type of training activity suitable following resistance exercise. Therefore, the primary aim of this thesis is to investigate the NM response during and following the type of maximum strength and power training sessions employed by elite athletes. However, in contrast to previous NM investigations, inducing fatigue is not the primary goal of the current investigations. Instead, the experimental approach was to compare the influence of different exercises, loads, and movement speeds upon acute NM response to these typical resistance exercise sessions.

The thesis investigates sessions comprising Olympic-style barbell resistance exercises, which are commonly used by elite athletes. Specific study of free-weight resistance exercise is warranted as differences in muscle activation levels between barbell versus machine exercise have been shown (Schwanbeck, Chilibeck, & Binsted, 2009). Furthermore, motor unit recruitment may be influenced by the task, in terms of the control

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of posture and support of load, such as in multi-joint barbell exercise (Mottram, Jakobi, Semmler, & Enoka, 2005). The specific study of elite athletes is also of interest, as strength-trained athletes elicit relatively greater acute responses to resistance exercise (Ahtiainen & Hakkinen, 2009). This maybe due to enhanced ability to tolerate training (Fry *et al.*, 1994) and increased NM recruitment (Aagaard, 2003; Aagaard *et al.*, 2002a; Hakkinen *et al.*, 1998). In addition, elite 'power' type athletes display specific NM performance capabilities (Tillin, Jimenez-Reyes, Pain, & Folland, 2010) that may influence the NM response to training sessions (Chiu, Fry, Schilling, Johnson, & Weiss, 2004; Chiu *et al.*, 2003).

To address the research aims outlined above a series of studies were designed. Firstly, the reliability sEMG and mechanical measurements during free-weight barbell resistance exercise was established. Then comparative studies comprising specific training sessions were conducted, using well-trained and elite subjects. The first study compares the difference in NM response between two multi-joint barbell exercises during a maximum strength type session. This was followed by comparison of NM response following maximum strength versus power type sessions, with matched barbell exercises and session volume. The final study compares the NM response to sessions of high intensity, explosive barbell exercise at three load levels, with similar total work. The following review of literature discusses the previous research underpinning the proposed investigations, and aims to establish the rationale for the methodological approach to the thesis.

Chapter One

Literature Review

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1. Literature Review

The following review of literature comprises two main sections. The first focuses upon the development and variety of neuromuscular fatigue research, which has provided insights of the magnitude and mechanisms underlying fatigue processes. This section also discusses the application of surface electromyography (sEMG), focusing upon the monitoring of fatigue during exercise. Part one concludes by discussing how these two research areas have been used to investigate resistance training. A critical review is made of the research to date, and arguments presented for the focus of the current thesis.

Part two discusses the fundamental science underpinning resistance exercise training. Beginning with a discussion of three distinct training types and the specific adaptations that result. This is followed by an overview of acute hormonal responses and the key mechanical variables that have been used to describe resistance exercise, as evidence suggests the hormonal response to and the mechanical characteristics of sessions may influence neuromuscular responses.

The review aims to demonstrate that research to date has not addressed the specific methods of strength and power training primarily used by elite athletes. It also argues that the combination of sEMG monitoring and neuromuscular assessments, along with mechanical descriptors of the exercises, provides a strong methodology for investigating the acute fatigue response to resistance exercise.

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1.1 Neuromuscular Fatigue

The definition of fatigue generally agreed upon in the neuromuscular (NM) literature, is a progressive reduction in the force or power generating capacity as a result of exercise (Cairns *et al.*, 2005; Enoka & Duchateau, 2008; Gandevia, 2001). Fatigue may be observed as the inability to maintain a sub-maximal level of force or power, or the inability to sustain maximum force or power. The definition of fatigue given implies it is a process, developing as exercise continues. This is distinct from the common usage of the term, which views fatigue as a singular moment of task failure or exhaustion. This would mean that during NM investigations, fatigue occurs only at the end-point of exercise. Instead, as Gandevia (2001) describes, fatigue is a process that begins from the onset, and progressively develops in proportion to the intensity of exercise. Importantly, exercise fatigue is reversible with rest, unlike clinical fatigue resulting from illness or injury.

NM fatigue investigations measure changes in force or power during or following exercise to describe the degree and rate of fatigue occurring. In physical terms, the magnitude of force determines the degree of change in momentum of an object that the force is acting upon. In other words, force is the amount of push or pull. During exercise, force may be measured in Newtons, as the outcome of a muscular contraction. Usually this is an isometric contraction performed within an apparatus where the subject can push against an unmovable resistance, which is measured by a force transducer or dynamometer device. Therefore, force is a direct and useful measurement to monitor NM fatigue (Gandevia, 2001). Power is defined the rate of change in energy, and is determined as the product of force and velocity, measured in Watts. Power describes both the degree of force generation and the speed of movement during dynamic exercise. Consequently, power is a measurement that represents the performance of dynamic contractions (Cairns *et al.,* 2005).

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In addition to the direct measurements of force and power, various NM measures have been used to investigate the mechanisms of fatigue. For example, sEMG is used to assess changes in motor unit recruitment (Adam & De Luca, 2005), trans-cranial magnetic stimulation can be used to detect exercise induced changes in cortical excitability (Goodall, Ross, & Romer, 2010; Taylor, Butler, Allen, & Gandevia, 1996) and evoked responses, such as passive twitch can be used to detect changes in the contractile function of the muscle (Edwards, Hill, & Jones, 1977; Morana & Perrey, 2009). This distinguishes the fatigue response, namely force or power changes, from the variables used to understand fatigue processes (Enoka & Duchateau, 2008). The challenge for the researcher is how to interpret the measurements in terms of underlying physiological processes (Cairns *et al.*, 2005). For example, changes in the sEMG signal amplitude merely indicate, and do not directly represent underlying changes in motor unit activation (Enoka & Fuglevand, 2001; Farina, Merletti, & Enoka, 2004).

Force is the outcome measure most commonly used by researchers and discussed in the sections 1.1.1 and 1.1.2. The discussion begins with the laboratory-based NM and sEMG investigations most relevant to resistance exercise and elite strength training. Applied exercise NM fatigue research is then discussed, such as cycling or sprinting (Bentley, Smith, Davie, & Zhou, 2000; Perrey *et al.*, 2010). The laboratory and applied research findings are compared and parallels drawn between them. Section 1.1.3 specifically addresses the previous NM fatigue research into resistance exercise and elite strength training.

Please refer to table 1.1 for definitions of the key terms and variables commonly used in the discussion of the literature.

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Table 1.1. Neuromuscular variables and terms defined.

Maximal voluntary contraction (MVC)	The maximum force or joint torque measured during an isometric test, such as elbow flexion or knee extensions (Gandevia, 2001). MVC is used as a performance outcome measure of exercise fatigue.
Voluntary activation (VA%)	A measurement used to represent muscle activation levels. It is calculated as the normalised additional force resulting from superimposed twitch stimulation of the MVC. Where, VA% = 100 x (1- (Superimposed Twitch Force / Resting Twitch Force)). It is related to the degree of descending neural drive, motor neuron output/excitability and spinal inhibition (Taylor & Gandevia, 2008).
Central Activation Ratio (CAR)	Another measure of muscle activation. It is processed from the ratio of MVC to the combined MVC and superimposed tetanic force (Kent-Braun & Le Blanc, 1996). Where, CAR= 100 x MVC / (MVC + Superimposed Tetanic Force). The combined force from the MVC and superimposed tetanus may represent true maximal force generation if a supra-maximal stimulation is applied to all motor units (Gandevia, 2001).
Evoked peak twitch force (Pt)	The force resulting from electrical stimulation of the passive, or relaxed muscle. The peak twitch measurement is obtained from a single and very brief electrical impulse (<5ms). Evoked forces from tetanic pulse trains (100-500ms) at different frequencies are also measured in NM investigations. Both peak twitch and tetanic force represent the contractile function of the muscle (Hill *et al.*, 2001).
Surface electromyographic (sEMG) amplitude	The sEMG amplitude is the detectable magnitude of electrical activity recorded on the surface of the active muscle. The processed sEMG amplitude value is used to represent the motor unit recruitment and/or firing rate (De Luca, 1997).
Peripheral fatigue	A neuromuscular fatigue response that is related to changes arising distal to neuromuscular junction (NMJ). These changes may include action potentiation propagation, excitation contraction coupling, cross bridge force generation, blood flow and substrate depletion and metabolite accumulation (Fitts, 1994).
Central fatigue	A fatigue response resulting in reduced motor unit activation (Babault *et al.*, 2006) arising proximal to the NMJ.

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1.1.1 Neuromuscular fatigue investigations

Early neuromuscular (NM) fatigue investigations used a combination of measurements during or following isometric exercise. For example, Merton (1954) measured the change in force resulting from a sustained maximal isometric voluntary contraction (MVC) of the isolated adductor pollicis muscle. A bespoke forearm dynamometer apparatus was constructed to perform and investigate the task, whilst photographs of oscilloscope readings were taken to analyse results. During the contraction, intermittent electrical stimulation, evoking a tetanic response, was superimposed on the adductor pollicis MVC and the amplitude of the sEMG signal from the muscle recorded. Merton (1954) found that the sustained MVC force reduced dramatically after a few seconds, and the superimposed tetanus did not further increase force, nor was there a reduction in sEMG amplitude. This was novel research that showed the severity and speed of fatigue resulting from the sustained MVC. It was concluded that peripheral fatigue occurred, as MVC reduced without changes in sEMG and stimulated force. The combination of MVC, evoked twitch, evoked tetani, superimposed stimulation, and sEMG measurements are typical of the NM assessment model still used today.

From these primitive technological beginnings, a body of NM research has evolved which has explored the mechanisms of fatigue. Kent-Braun (1999) argued that the combination of different technologies 'allows for the simultaneous quantifying of the relative roles of central and peripheral factors in fatigue'. In this way, researchers have used a battery of variables that each represents different sites in the NM system. The relative changes of the variables compared to each other enables an interpretation of the mechanisms of fatigue. For example, the original research by Merton (1954) found a reduction in MVC, which represents the whole NM system, along with no change in the superimposed force increment. As the degree of superimposed increment represents central drive to the

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muscle, the logical conclusion was that fatigue was caused by peripheral factors. Historically, two methodological approaches have been employed; either intermittent assessment throughout the fatiguing task (Bigland-Ritchie, Cafarelli, & Vollestad, 1986; Bigland-Ritchie, Furbush, & Woods, 1986; Sogaard *et al.*, 2006), or a comparison of assessment changes pre- versus post task (Gandevia, Allen, Butler, & Taylor, 1996; Kent-Braun, 1999; Taylor *et al.*, 1996). The research has mainly investigated the relative contribution of the peripheral and central sites of the NM system to the fatigue process. Figure 1.1 depicts some of the key sites of the NM system. Specifically, the border between central and peripheral NM system is defined as the neuromuscular junction (NMJ).

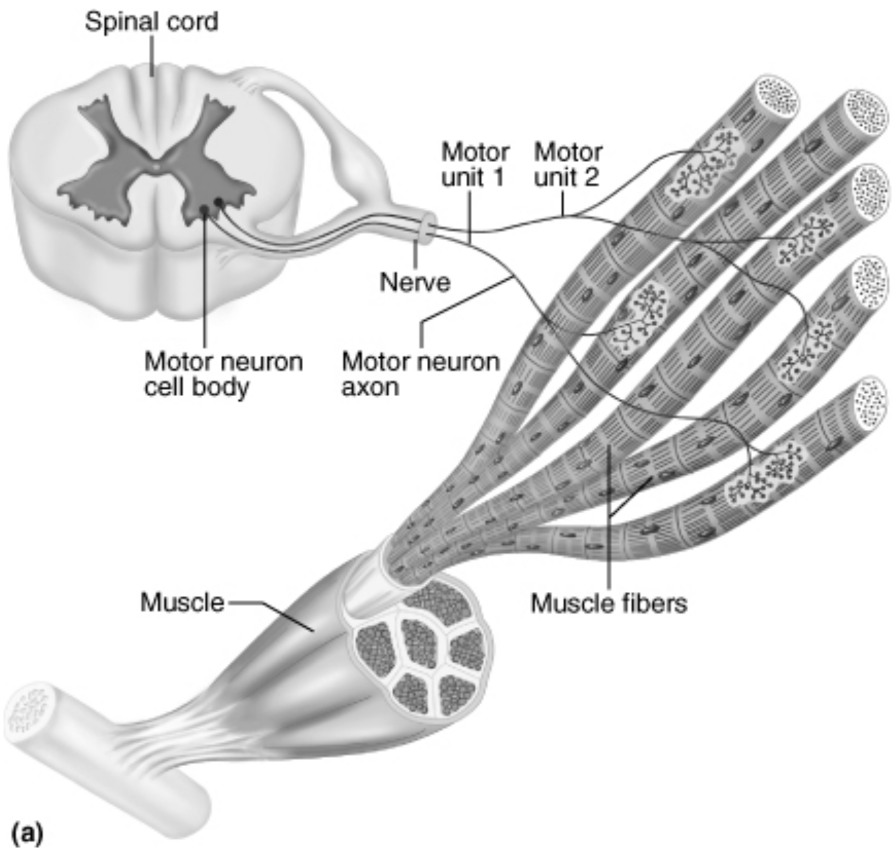

Figure 1.1. The neuromuscular system (adapted from Marieb & Hoehn, 2010).
The NM system is shown from the spinal cord downwards, with cortical areas not represented. The NMJ is depicted as the dots joining the motor neuron axons to the muscle fibres. The NMJ is considered as the border between the central and peripheral NM system.

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1.1.1.1 Investigations into central and peripheral fatigue mechanisms

Evidence of central fatigue comes from research that has found reductions in MVC accompanied by reductions in VA%, the latter representing processes upstream of NMJ (Taylor & Gandevia, 2008). For example Gandevia *et al.* (1996) found MVC and VA% reduced by 60 and 10% respectively following two minutes of sustained MVC elbow flexion exercise, which was supported by research from Todd *et al.* (2007). A reduction in VA% specifically means greater additional force results from a superimposed stimulation made during the MVC force assessment. As the stimulation is direct to the muscle, a greater additional superimposed force means that maximum voluntary effort results in relatively less force generation capacity. This implies a reduction in central activation of the muscle. Evidence suggests motor neuron firing rate is a key mechanism explaining changes in VA% (Taylor & Gandevia, 2008). Firing rates have been consistently found to slow under fatigue (Bigland-Ritchie, Thomas, Rice, Howarth, & Woods, 1992). This reduced motor neuron firing rate would limit the force measured during the maximal voluntary, but not superimposed force assessment.

Reduced motor neuron firing rates may result from three distinct locations in the NM system. Firstly, a reduction in descending efferent drive from the motor cortex may reduce the excitation of the motor neurons. Evidence for this comes from superimposed additional force increasing as a result of trans-cranial magnetic stimulation (Gandevia *et al.*, 1996; Taylor, Allen, Butler, & Gandevia, 2000). Secondly, reduced motor neuron excitability at the synapse of the motor axon reduces the responsiveness to descending drive, thereby reducing motor neuron firing (Martin, Gandevia, & Taylor, 2006). Finally, increased inhibition at the spinal level from small diameter (type III & IV) afferent feedback related to metabolite and blood flow changes during fatiguing contractions (Gandevia *et al.*, 1996; Rotto & Kaufman, 1988). Therefore, change in VA% indicates a

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number of possible spinal or supraspinal processes resulting in reduced muscle activation (Sogaard et al., 2006). This means that the VA% variable is not synonymous with central fatigue, but merely indicates possible central fatigue processes (Gandevia, 2001).

Other research has shown evidence of peripheral fatigue mechanisms following sustained isometric force tasks. Bigland-Ritchie, Cafarelli, *et al.* (1986) found that following 30 minutes of intermittent submaximal (30% MVC) quadriceps contractions both MVC and evoked peak twitch force declined by 50%. During the contractions sEMG amplitude increased due to additional recruitment of non-fatigued motor units. In addition, there were no changes to muscle lactate, pH, and ATP concentrations along with minimal glycogen depletion, suggesting limited metabolic changes as a result of the exercise. Bigland-Ritchie, Cafarelli, *et al.* (1986) concluded peripheral fatigue had occurred, based upon the similar change in both MVC and evoked peak twitch (Pt) assessments. The reduced MVC represents change at any part of the peripheral and central NM system (Taylor & Gandevia, 2008). In contrast, reduced Pt only represents the peripheral contractile changes distal to the NMJ (Fowles & Green, 2003). Specifically, the evoked twitch may represent sarcoplasmic reticulum changes affecting excitation-contraction coupling (E-C coupling) as a result of impaired Ca^{2+} release or contractile sensitivity to Ca^{2+} (Hill, Thompson, Ruell, Thom, & White, 2001). Therefore, as MVC and evoked twitch reduced to the same degree, fatigue was peripheral and associated with the E-C coupling mechanism. A limitation of this study was that Bigland-Ritchie, Cafarelli, *et al.* (1986) did not include the VA% variable in their assessment battery and conclusions were based upon the relative change in MVC and Pt. However, Pt may be influenced by possible post activation potentiation as well as fatigue (Fowles & Green, 2003; Gossen & Sale, 2000; Morana & Perrey, 2009). For example, fatigue has been shown to progressively increase with 10 minutes of repetitive contractions demonstrated by reduced

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MVC and changes to sEMG responses, whilst Pt was increased throughout, as a result of concurrent potentiation (Morana & Perrey, 2009). This is because muscle contractions result in increase phosphorylation of the myosin light chains, which results in greater force resulting from similar Ca^{2+} release. In other words more effective E-C coupling, which may be reflected in Pt assessment. (See section 1.1.3.2 for a full discussion of potentiation effects). Therefore, a study relying solely upon comparisons between Pt and MVC may misinterpret the degree of peripheral and/or central fatigue.

Bigland-Ritchie, Furbush, *et al.* (1986) further investigated NM fatigue using MVC, %VA, and Pt assessments during repetitive submaximal quadriceps contractions (6s at 50% MVC with 4s rest). MVC force declined throughout exercise along with evoked twitch force. There were no changes in VA% or sEMG amplitude during the MVC test. In contrast the sEMG amplitude recorded during the contractions increased throughout the trial, reaching maximal at the end, which reflects increasing motor unit recruitment. In combination, these results suggested central factors did not limit MVC. The VA% was unchanged, whilst Pt, which represents the peripheral NM system, reduced concurrently with MVC. In addition, whilst not directly comparable, the increased sEMG amplitude during the fatiguing trial implies motor unit recruitment increased, suggesting a NM strategy to maintain force generation under increasing fatigue (Bigland-Ritchie, Cafarelli, *et al.*, 1986). In contrast to the previous study, the conclusion was based upon a balanced analysis of variables representing the NM system globally (MVC), peripherally (Pt) and centrally (sEMG amplitude and VA%). This leads to greater confidence that the mechanisms of fatigue have been correctly interpreted, compared to studies relying upon only peripheral (Bigland-Ritchie, Cafarelli, *et al.*, 1986) or central (Gandevia *et al.*, 1996; Taylor *et al.*, 1996) measures.

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Klass *et al.* (2004) also used a comprehensive NM assessment battery to assess fatigue following dynamic calf exercise, comprising MVC, Pt, VA%, and sEMG amplitude. A further strength of this study was the normalisation of sEMG amplitude with evoked M-wave, which allowed for an accurate interpretation of the sEMG amplitude in terms of whether peripheral changes have influenced the signal (Klass *et al.*, 2004; Perrey *et al.*, 2010), see section 1.1.2 for more detail. Submaximal plantar flexion (50% MVC) was performed until failure. This resulted in reduced MVC and Pt, whilst VA%, M-wave, and sEMG to M-wave ratio were unchanged post exercise. Similar to the isometric studies above (Bigland-Ritchie, Cafarelli, *et al.*, 1986; Bigland-Ritchie, Furbush, *et al.*, 1986), these findings suggest peripheral mechanisms dominate the fatigue process. The unchanged M-wave value suggested action potential propagation and NMJ excitability were unchanged (Fitts, 1994; Perrey *et al.*, 2010) which increased confidence that sEMG represented motor unit activation and not peripheral muscle changes.

Kent-Braun (1999) induced fatigue with four minutes of sustained MVC dorsi flexion. They found MVC decreased by 22%, evoked twitch force by 30% and CAR reduced from 94 to 78% and sEMG amplitude during MVC reduced from 100% to 73% without any change in M-wave amplitude. In addition they showed decreased muscle pH, suggesting significant local muscle fibre fatigue had occurred. In this study, evidence of both central (CAR and sEMG amplitude reduced) and peripheral (Pt and pH changes) mechanisms contributed to the reduced MVC post exercise. In fact, based upon the degree of reduction in Pt and CAR relative to change in MVC they estimated 20% of the reduced force generation capacity was due to central factors. Kent-Braun (1999) suggested that CAR was a more sensitive measure of fatigue than VA%. This is because the tetanic train stimuli used in the CAR technique results in greater additional force superimposed upon the MVC compared to the single and double twitch stimuli typically used in VA%

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measurements (Kent-Braun & Le Blanc, 1996). Consequently, previous studies using VA% may have missed evidence for central fatigue (Bigland-Ritchie, Furbush, *et al.*, 1986). However, it is also likely that the sustained MVC protocol significantly influenced the NM response, as VA% is consistently reduced following maximal tasks (Gandevia *et al.*, 1996; Taylor *et al.*, 1996; Todd *et al.*, 2007). Therefore the finding was task, and not methodology related.

The balance between central and peripheral fatigue has been shown to vary in relation to the type of exercise task. Behm & St-Pierre (1997) compared the quadriceps fatigue response to a long duration protocol at 25% MVC and a short duration protocol at 50% MVC. Both protocols involved intermittent 10 s contractions until the target MVC force could not be maintained. The long duration 25% MVC protocol was maintained for 20 minutes compared to 4 minutes for the short duration 50% MVC protocol. Following both of these fatiguing protocols they found MVC, Pt and VA% were reduced. Specifically, MVC reduced 40% following the long duration protocol and 30% following the short duration protocol. VA% also reduced more following the long duration protocol (-13% versus -6%). The finding that VA% reduced twice as much following the long duration protocol suggests different levels of change in central versus peripheral fatigue. This finding was supported by Yoon *et al.* (2007), who found greater reduction in VA% following a long duration low force versus a short high force task, with similar reductions in Pt following both tasks.

Sogaard *et al.* (2006) provided evidence that peripheral and central fatigue may recover at different rates. They measured intermittent MVC, VA% and twitch assessments throughout 43 minutes of 15% MVC isometric elbow flexion. Post exercise MVC and Pt were reduced by 40% showing force generation capacity reduced. During the task sEMG

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amplitude increased, suggesting increased motor unit recruitment to compensate for local muscle fatigue. VA% decreased pre versus immediately post exercise (98% versus 72%), as did sEMG amplitude during MVC. MVC partially recovered towards pre values 10 and 25 minutes post exercise, whilst VA% and sEMG amplitude during MVC had recovered within 10 minutes. In contrast, Pt had not recovered 25 minutes post exercise. This suggested central fatigue recovers relatively quickly (Behm *et al.,* 1997) allowing for partial recovery of MVC despite prolonged contractile impairment.

This discussion aimed to establish that the nature of NM fatigue is specific to the duration and intensity of exercise performed. In addition, there is evidence that NM fatigue is specific to the contraction type of the exercise task, as well as the intensity and duration. For example, Kay, St Clair Gibson, Mitchell, Lambert, & Noakes (2000) compared isometric with dynamic concentric tasks. MVC was reduced following both isometric and concentric tasks, but sEMG amplitude during MVC only reduced following isometric exercise. Further evidence for specific contraction type responses comes from Babault *et al.* (2006), who compared three 30s maximal concentric knee extension exercise with three sustained isometric MVC knee extensions. Both protocols were designed to result in similar levels of fatigue, as measured by MVC force. VA% decreased more during the isometric trial across all three sets. In addition, sEMG amplitude during MVC did not change following the concentric sets, but was reduced following isometric, similar to Kay *et al.* (2000). These findings suggest both maximal concentric and maximal isometric exercise leads to central fatigue, but that greater central changes occur following isometric exercise. This is explained by the higher levels of ischemia resulting from the isometric exercise influencing metabolite accumulation, which in turn resulted in greater inhibition of motor neuron output via small diameter (type III and IV) afferents (Babault *et al.*, 2006). In contrast to the VA% findings, Pt reduced significantly after set one of concentric

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exercise and remained reduced, whereas as Pt reduced progressively across the three sets of isometric exercise. This suggests changes in Ca^{2+} release and re-uptake leading to impairment in E-C coupling occurs more quickly following concentric exercise. Overall, this study is important as it established that the nature of fatigue differed between isometric and dynamic exercise conditions despite similar force decrement post both exercise conditions.

In summary, NM fatigue investigations have revealed some interesting and diverse findings regarding central versus peripheral sites of the NM system leading to fatigue. When a comprehensive NM assessment model was utilised, comparisons between variables reveal the relative contribution of peripheral and central fatigue (Kent-Braun, 1999). In addition, studies that utilised more variables (Sogaard *et al.*, 2006), were able to draw more robust or detailed conclusions, particularly compared to limited or imbalanced assessment models representing only one side of the NM system (Bigland-Ritchie, Cafarelli, *et al.*, 1986; Taylor *et al.*, 1996).

An overview of the research suggests that sustained maximal isometric exercise induces some degree of central fatigue (Kent-Braun, 1999; Taylor *et al.*, 1996), but peripheral fatigue will be the major contributor to the overall fatigue outcome following high force tasks (Yoon *et al.*, 2007). Specifically, decreased cortical and motor neuron output combined with significant peripheral force contractile deficits. Following long duration, low force exercise tasks central and peripheral fatigue appears more balanced (Behm & St-Pierre, 1997; Sogaard *et al.*, 2006). Following relative moderate duration and moderate force tasks (e.g. 50% MVC) peripheral fatigue seems to dominate, with little evidence of central fatigue (Bigland-Ritchie, Furbush, *et al.*, 1986; Klass *et al.*, 2004). Furthermore, some studies show that the recovery of the variables representing the peripheral and central

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NM system may differ (Sogaard *et al.*, 2006), with good evidence that central fatigue mechanisms can recover quickly (Taylor *et al.*, 1996). Lastly, submaximal dynamic exercise tasks result in primarily peripheral fatigue, perhaps due to the similarity to the moderate force, intermittent isometric condition. Maximal dynamic tasks, result in less central fatigue in comparison to maximal isometric exercise (Babault *et al.,* 2006). Together these findings show that the intensity, duration and contraction type of exercise might influence the fatigue response.

The specificity of the findings into NM fatigue response underpins the rationale for the present thesis. Maximal and submaximal contractions of different intensity and duration result in different NM fatigue responses in isometric and dynamic contractions. Resistance exercise involves repetitive dynamic contractions of variable intensity from sub-maximal to maximal, depending upon the training goal. Resistance exercise intensity is defined as the load, and also the speed at which the load is moved. For example, sessions designed for maximum strength improvement involve near maximal loads, whilst sessions designed to improve power involve moderate loads performed quickly. Session duration may also vary and is also specific to the goal of the structured session. Typically sessions are constructed into a series of sets of repetitions of one or more resistance exercises with rest intervals between sets. Sessions to improve hypertrophy involve greater sets and repetitions than session for maximum strength.

The NM research investigating dynamic contractions may not specifically inform the degree and nature of NM fatigue following entire resistance exercise sessions. This is due to the variation in intensity and duration between session types and the intermittent nature of entire sessions, in contrast to single bouts of repetitive or sustained contractions performed to fatigue. In addition, training for athletic performance commonly involves

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specific whole body barbell, or free-weight, resistance exercises. This involves the support of ones' body weight, the control of posture as well as lifting the load. Strong evidence exists showing how the control of position and posture, in addition to maintaining contraction force influences NM fatigue response (S. K. Hunter, Duchateau, & Enoka, 2004; Maluf & Enoka, 2005). Therefore, previous NM fatigue investigations of machine isolated-joint dynamic contractions may not fully inform us of the specific response to typical elite athlete training methods. As a result of the variation and specific nature of structure resistance exercise sessions, investigations into the NM fatigue response are of interest. Specifically, comparisons between sessions using different resistance exercises and/or different sessions of distinct intensity and duration may reveal specific responses in NM fatigue (Chiu *et al.*, 2004; Klass *et al.*, 2004; Smilios *et al.*, 2010).

1.1.1.2 Applied research investigating neuromuscular fatigue

Over the last decade, the same methodological approach has been used to assess the NM response to applied exercise. Fatigue was measured using pre- versus post-exercise NM assessments, with running or cycling replacing the isometric force tasks, for example. Bentley *et al.* (2000) measured MVC, CAR, sEMG amplitude during MVC 10 minutes, 30 minutes and 6 hours following 30 minutes of high intensity cycling exercise (80% VO_2max) plus 4 x 1 minute cycle maximal sprints. They found evidence of long lasting central fatigue (30 minutes and 6 hours post exercise). Supporting this finding, Place, Lepers, Deley, & Millet (2004) found VA% was reduced 10 minutes following endurance running exercise. Relating this back to the isometric research, the evidence of central fatigue was most clear following long duration & low force tasks (Behm & St-Pierre, 1997; Sogaard *et al.*, 2006; Yoon *et al.*, 2007). However, in these studies there was faster recovery of central fatigue (within minutes) compared to peripheral fatigue (Sogaard *et al.*, 2006).

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Central fatigue has been shown following endurance exercise comprising repetitive cycle sprints shown by decreased MVC, VA% and sEMG amplitude during MVC (Racinais *et al.*, 2007; Zory, Weist, Malakieh, & Grenier, 2010). Reduced CAR following endurance exercise in the heat has also provided evidence of central fatigue (Nybo & Nielsen, 2001; Saboisky, Marino, Kay, & Cannon, 2003). This may relate to the central-governor model of fatigue (Noakes, 2000), which argues that the brain protects the organism against threat by down-regulating biological systems. For example, Noakes, Peltonen, & Rusko (2001) show that cardiac function is protected when exercising at high altitude via autonomic lowering of cardiac output. The descending efferent drive to the muscles may be altered via higher cortical areas (Noakes, 2000) and via changes in neurotransmitter concentrations (Blomstrand, Ek, & Newsholme, 1996; Newsholme & Blomstrand, 1996). Therefore VA% and CAR may change as a result of prolonged exercise, and/or environmental factors, influencing physiological systems.

In summary in would appear that endurance exercise induces fatigue with central mechanisms. However, the investigations discussed above do not include Pt as a variable representing peripheral fatigue, nor was sEMG amplitude normalised to the M-wave in most cases. Therefore, conclusions as to the precise balance between peripheral and central fatigue mechanisms are limited.

In contrast, peripheral fatigue mechanisms seem to mostly occur following high intensity sprint exercise. Billaut & Basset (2007) found that whilst MVC was reduced following cycle sprints, the sEMG amplitude during MVC increased. This implies peripheral muscle fatigue as increased motor unit recruitment compensated for loss of force (Adam & De Luca, 2005). However, these conclusions are based upon a limited set of NM assessments.

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A more comprehensive methodology was used to study sprint running by Lattier, Millet, Martin, & Martin (2004). The researchers found that following treadmill running sprints both MVC and evoked twitch force decreased, whilst there was no change in VA% and sEMG amplitude (normalised by M-wave). This set of findings suggests there was no change in NMJ action potential propagation (M-wave) or motor unit activation (VA% and sEMG). Consequently a disruption in the E-C coupling (Pt) was the likely cause of fatigue. Following these findings Perrey *et al.* (2010) examined the response following a session comprising 12 x 40 m sprints, with 30 seconds rest between runs. The post session testing occurred two minutes after the 12th sprint and comprised soleus muscle M-wave, sEMG amplitude, Pt, MVC, and VA%. Running performance decreased during the session, accompanied by increased blood lactate concentrations, demonstrating fatigue occurred. Post session assessments showed reduced MVC (-11%), VA% (-2.7%) and Pt (-13%), whilst sEMG (normalised by M-wave) during MVC remained unchanged. This provided mixed and weak evidence for central fatigue as the small reduction in VA% suggests a decrease in voluntary drive, but no change in sEMG amplitude suggests motor unit recruitment was not affected (Perrey *et al.*, 2010). The greatest decrease was found in Pt, representing E-C coupling change, and suggests peripheral fatigue was the biggest factor in the reduced MVC and sprint performance. Specific evidence that E-C coupling had changed supported this suggestion, as 20Hz tetanic twitch force decreased more than 80Hz force following the session, which is indicative of E-C coupling dysfunction (Fowles & Green, 2003; Jones, 1996). In contrast, limited changes to M-wave and H-reflex suggested stable NMJ transmission and action potential propagation, further pinpointing fatigue towards the E-C coupling mechanism. Interestingly, all variables were restored to baseline following 30 minutes of recovery, which contrasts with the response found following fatiguing endurance cycling exercise (Bentley *et al.*, 2000). Further evidence that the peripheral NM system is the dominant fatigue site following high intensity

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exercise comes from a study of jump training that showed reduced Pt and MVC (Drinkwater, Lane, & Cannon, 2009). They also concluded E-C coupling was a likely cause of fatigue, however no sEMG or VA% tests were performed in this study, limiting the evidence.

The NM fatigue following team sports, such as football and handball, has shown reduced MVC, sEMG amplitude during MVC and rate of force development (RFD) (Thorlund, Aagaard, & Madsen, 2009; Thorlund, Michalsik, Madsen, & Aagaard, 2008). These findings suggest reduced muscle activation based upon the established link between motor unit recruitment and force development, particularly early onset activation (Aagaard *et al.*, 2002a; Van Cutsem *et al.*, 1998). These findings infer central fatigue from the reduced activation. However, CAR, VA% or Pt assessments were not used, also limiting the findings.

The NM assessment model discussed above has also been applied to resistance exercise. Behm *et al.* (2002) compared the NM response to one maximal set of 20, 10 or 5 repetitions of elbow flexion. They found no change in MVC or VA%, but Pt was reduced and remained suppressed for three minutes following each set. Furthermore, 20 repetitions resulted in greater Pt decrement. This finding was similar to those that found sustained submaximal isometric forces resulted in predominantly peripheral fatigue (Bigland-Ritchie, Cafarelli, *et al.*, 1986; Bigland-Ritchie, Furbush, *et al.*, 1986; Klass *et al.*, 2004). However, as explained above, single sets of a resistance exercise and entire sessions are not the same in terms of structure and duration and may vary in intensity depending upon the training goal. Unfortunately, few investigations have assessed entire strength sessions (Tran *et al.*, 2006). The body of research to date will be critically discussed in section 1.1.3.

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In summary, there is evidence that specific exercise type, intensity and duration leads to specific NM fatigue responses. Endurance exercise seems to lead to central fatigue, similar to findings following prolonged low force tasks. Sprint type exercise, by contrast, seems to result in a peripheral fatigue response, also shown following moderate and intermittent force tasks. To date, there is no established body of evidence comprehensively describing the NM response to entire resistance exercise sessions.

1.1.1.3 Neuromuscular assessment variables.

The discussion of NM investigations have used combinations of MVC, CAR or VA%, Pt and sEMG amplitude (Kent-Braun, 1999). This section critically evaluates these variables from a methodological viewpoint.

Maximal Voluntary Contraction:

The MVC force assessment is the cornerstone of most NM fatigue research. This assessment is a valid assessment of the force generating capacity of the muscle under investigation and it represents the entire NM system (Taylor & Gandevia, 2008). The MVC has been shown to be sensitive to differences in metabolic processes following repetitive fatiguing contractions, suggesting it is suitable for fatigue investigations (McNeil, Murray, & Rice, 2006). MVC also enables VA% or CAR to be measured relative to maximal voluntary drive, through the comparison to maximal evoked force due to superimposed stimulation (Gandevia, 2001). The MVC test is commonly used to measure fatigue induced changes in motor unit recruitment and/or firing rates using sEMG (De Luca, 1997; Taylor & Gandevia, 2008). It is a suitable test to assess these changes, as voluntary effort is maximal and constant between fatigued and non-fatigued tests. Therefore, any recruitment or firing rate changes are attributable to fatigue and not effort. To ensure this validity, it is recommended that researchers purposefully ensure consistent

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performance from subjects, providing clear test instructions, verbal encouragement to give maximum effort and also feedback of results (Gandevia, 2001; Kent-Braun & Le Blanc, 1996).

Investigations have established good levels of reliability (Allen, Gandevia, & McKenzie, 1995; Zech, Witte, & Pfeifer, 2008), with between-trial intraclass correlation coefficient of r = 0.99 and coefficient of variation of 3.8% (Allen *et al.*, 1995). Therefore MVC is a reliable measurement appropriate for NM research. However, there are considerations for the interpretation of MVC assessments in physiological terms. Firstly, MVC may reflect the status of both central and peripheral NM system. Combining MVC with Pt and VA% or CAR assessments can provide information to help determine the balance of between central and peripheral fatigue (Kent-Braun, 1999). A second consideration is the degree of antagonist muscle co-contraction during the execution of the test. The resultant measurement of the MVC is the net torque around the joint, not simply the force due to the agonist muscle. This means that changes in MVC scores may be due to variation in antagonist muscle influencing net joint torque, and not the agonist muscle under investigation. Monitoring the antagonist muscle and any relative change compared to the agonist is therefore recommended, as this can be influenced by fatigue (De Luca, 1997; Weir, Keefe, Eaton, Augustine, & Tobin, 1998; Zory *et al.*, 2010).

Evoked Peak Twitch Force:

Evoked force is defined as the peak twitch force (Pt) in response to an electrical stimulus. Specifically it is the measured joint torque resulting from the percutaneous stimulation of the passive (relaxed) muscle. Typically, the twitch stimulus is a very brief (< 1 ms) single pulse of 200-400V (Behm *et al* 1997; Morana & Perrey, 2009). This differs from evoked tetanic force, which involves prolonged (1 s) stimulation at a range of frequencies (Fowles

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& Green, 2003). The Pt of the quadriceps (knee extension force) has been shown to have high reliability with between-trial coefficient of variation of 5.1% and intraclass correlation coefficient of r = 0.97 (Allen *et al.*, 1995) and between-trial coefficient of variation of 5.6% and intraclass correlation coefficient of r = 0.92 (Place, Maffiuletti, Martin, & Lepers, 2007). Between and within day 95% repeatability coefficients were also demonstrated across seven days of Pt post fatiguing exercise (Morton *et al.*, 2005). The reliability of the Pt variable was found to be similar between potentiated or un-potentiated stimuli (Kufel, Pineda, & Mador, 2002). However, potentiated assessments may be more sensitive to fatigue. This is because the comparing of Pt values post fatigue with the pre-fatigued condition ideally requires the same degree of potentiation in both conditions. Therefore, comparing potentiated twitches may help to isolate fatigue (Kufel *et al.*, 2002; Place *et al.*, 2007).

The interpretation of Pt is not straightforward. This is because the Pt measurement is the net result of potentiation and fatigue at the time of test (Fowles & Green, 2003; Perrey *et al.*, 2010). Fowles & Green (2003) explain how Pt may be influenced by increased cross bridge formation resulting from myosin light chain phosphorylation due to post-activation potentiation (Vandenboom, Grange, & Houston, 1995; Vandervoort, Quinlan, & McComas, 1983) and the dysfunction in E-C coupling that results from changes in Ca^{2+} release in the sarcoplasmic reticulum (Hill *et al.*, 2001). The E-C coupling dysfunction identified by reduced Pt is often referred to as low frequency fatigue (Edwards *et al.*, 1977; Jones, 1996). The problem of concurrent potentiation and fatigue confounding Pt measurements may be overcome by ensuring the Pt measurement is taken a few minutes post the contraction (or exercise bout). This is because low frequency fatigue is long lasting whereas as potentiation declines within minutes (Fowles & Green, 2003; Morana & Perrey, 2009). It is also recommended that the rate of twitch development be also

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processed from evoked twitch assessment, as this may be more representative of potentiation and does not reflect low frequency fatigue (Fowles & Green, 2003). Additionally, tetanic force measurements of low frequency (e.g. <30Hz) can also confirm the presence or not low frequency fatigue versus potentiation (Perrey *et al.,* 2010). In summary, evoked twitch force is a reliable variable that can provide specific information about the fatigue response, but one that must be interpreted with caution.

Voluntary Activation and Central Activation Ratio:

VA% and CAR are determined with different methodologies. VA% is more common and calculated from the formula: 1 - (superimposed twitch force / resting evoked twitch force) (Babault, Pousson, Ballay, & van Hoecke, 2001; Behm & St-Pierre, 1997; Bigland-Ritchie, Furbush, *et al.*, 1986; Klass *et al.*, 2004). The superimposed twitch results in an increment in force over the MVC force level. The formula is based upon the inverse relationship between the increment in force resulting from the superimposed stimulus and the initial level of muscle force, first shown by Merton (1954). In contrast, CAR is calculated as the ratio of MVC force / (MVC force + superimposed tetanic force). VA% and CAR are typically both assessed on quadriceps muscle and knee extension MVC force assessment.

The two methods have been shown to be correlated under fresh conditions (r = 0.9 - 0.96) (Bilodeau, 2006). The VA% variable may reduce more with fatigue, although both VA% and CAR remained well correlated under fatigue (r = 0.83) (Bilodeau, 2006). This finding contradicts the suggestion by Kent-Braun (1999) that CAR was more sensitive to central fatigue than VA%. This was based upon a previous study, which established the sensitivity of CAR but did not compare it to VA% (Kent-Braun & Le Blanc, 1996). However, CAR may have advantages over VA% as it is established directly from the MVC and superimposed tetanic force, which are measured during a single test. Therefore the

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ratio is established from comparable conditions (Bilodeau, 2006). In contrast, VA% requires a second twitch assessment to compare with superimposed force increment. This second test may vary in terms of muscle function (Bilodeau, 2006), specifically as a result of whether it is performed pre versus post the maximal assessment (Folland & Williams, 2007). VA% is further complicated by evidence that shows a non-linear relationship between the proportion of MVC and possible superimposed force increment (Folland & Williams, 2007). Hence the simple CAR ratio may be a more suitable test than the more commonly used VA% (Schillings, Stegeman, & Zwarts, 2005).

VA% has been shown to have good reliability, with between-trial intraclass correlation coefficient of r = 0.86 and coefficient of variation of 1.4% (Allen *et al.*, 1995). Between-trial intraclass correlation coefficient of r > 0.9 have also been reported (Zech *et al.*, 2008). The CAR variable has also been shown to have good reliability, with between-trial coefficient of variation of 1.2% (Place *et al.*, 2007). A further methodological recommendation is that the superimposed stimulation used during VA% or CAR should comprise pulse trains and not single twitch stimulations (Folland & Williams, 2007; Kent-Braun & Le Blanc, 1996; Lexell & Miller, 2009), as this will ensure greater sensitivity to change.

In terms of understanding what VA% or CAR represents, Gandevia (2001) explains how either spinal or supraspinal factors can contribute to the value measured. This may involve reduced descending efferent drive (Gandevia, 1996) or increased spinal inhibition or reduced responsiveness of motor neurons at the synapse (Martin *et al.*, 2006). However, the addition of trans-cranial magnetic stimulation of the motor cortex and motor evoked potential assessments been used to provide information on the location of change (Sogaard *et al.*, 2006; Taylor & Gandevia, 2008). Therefore, VA% or CAR is not directly equated

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to central fatigue. Instead, they indicate the presence of central fatigue, which may result from various sites proximal to the NMJ. A second consideration is that the electrical stimulation method typically used to elicit CAR or VA% does not induce activation of all available motor units in a muscle group, as has been recently revealed by MRI investigations (Kendall, Black, Elder, Gorgey, & Dudley, 2006). In particular, the deep lying motor units may not be activated. Therefore, researchers may not assume the outcome measurement represents VA% in a literal manner. It is preferable to view CAR or VA% as representing the possible percentage of force generation available, rather than exact proportion of motor unit activation occurring.

Despite these limitations, the use of VA% and CAR variables are supported in the literature as they are reliable and sensitive to change (Taylor, 2009) which enables their use in repeated measured design studies (Racinais & Girard, 2009). Therefore, the main purpose of the measurement is to assess relative changes in activation levels, rather than establishing the actual magnitude of motor unit activation. For the measurement to be informative, the only requirement is that the same level of incomplete superimposed activation occurred pre and post exercise (Nybo & Nielsen, 2001). The CAR or VA% can therefore be used as an indicator of changes in central fatigue, but cannot differentiate between spinal and cortical levels (Paillard, Noe, Passelergue, & Dupui, 2005). For methodological ease, as the choice is balanced, CAR is used in this thesis.

1.1.1.4 Neuromuscular fatigue investigations summary

NM fatigue investigations in both laboratory and applied settings have yielded interesting results regarding the magnitude and nature of fatigue. The responses are clearly specific to exercise task, such as the relative intensity and duration (Yoon *et al.*, 2007). A case has been made for the use of a varied and balanced assessment battery (Kent-Braun, 1999),

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including MVC, CAR or VA%, Pt, and sEMG during MVC. Investigations that have used this combined methodology have revealed insightful findings as to the NM fatigue following applied exercise (Bentley *et al.*, 2000; Lattier *et al.*, 2004).

The research suggests that two general kinds of fatigue response exist. The first involves central and peripheral mechanisms and results from long duration, low force exercise (Behm & St-Pierre, 1997) and endurance exercise (Bentley *et al.*, 2000). The second type involves mostly peripheral fatigue and results from moderate and high intensity force tasks (Bigland-Ritchie, Furbush, *et al.*, 1986) and sprinting (Drinkwater *et al.*, 2009; Perrey *et al.*, 2010). In relation to the present thesis, as the NM response is specific to exercise type, intensity and duration, it would be informative to conduct NM investigations of structured sessions of resistance exercises used by elite athletes to develop strength and power. Currently, the research only informs us of the NM responses from isolated isometric and single joint dynamic exercise research, which is distinct from elite athletes performing entire strength training sessions. For example, athletes typically conduct a series of two or more multi-joint barbell exercises constructed into sets of repetitions with fixed rest intervals between sets. The intensity of the load (force) varies inversely with the number of repetitions performed during the set. Therefore the nature and structure of elite strength and power training sessions are quite distinct from the single bouts of exercise that have been typically investigated. Section 1.1.3 will critically discuss the previous research investigating fatigue following resistance exercise sessions. A case is made for the NM assessment model reviewed in this section to be used for strength and power training investigations. Beforehand, the application of sEMG analysis to fatigue research, and specifically resistance exercise will be discussed.

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1.1.2 Applications of sEMG to neuromuscular fatigue

Surface EMG has been used in biomechanics and kinesiology research, due to the relationship between muscle force and sEMG amplitude (De Luca, 1997). For example, there is a close relationship between knee extension isometric force and quadriceps muscle sEMG amplitude (Alkner, Tesch, & Berg, 2000), explained by increased motor unit firing rates to provide increased muscle force (Conwit *et al.*, 1998). This demonstrates the influence of motor neuron output on force generation. Examples of biomechanical sEMG applications include investigations of comparative sEMG amplitude during different exercises, such as squat and jumping (Caterisano *et al.*, 2002; Ebben, Simenz, & Jensen, 2008; Escamilla *et al.*, 1998) and analysis of muscle activity patterns during walking and running gait in relation to kinematic and kinetic variables (Mann, Moran, & Dougherty, 1986; Antti Mero & Komi, 1987; Novacheck, 1998). Surface EMG has also been applied to fatigue investigations by physiology researchers (A. M. Hunter, De Vito, Bolger, Mullany, & Galloway, 2009; Moritani *et al.*, 1986; Stafford & Petrofsky, 1981). The sEMG response associated with fatigue has been differentiated between maximal and submaximal isometric exercise (Moritani *et al.*, 1986). Furthermore, the response to fatiguing dynamic contractions has been shown to be specific (Kay *et al.*, 2000).

Moritani *et al.* (1986) studied the sEMG amplitude and frequency response to isometric elbow flexion performed at MVC and 50% MVC force levels. During MVC both amplitude and frequency significantly reduced with force levels. In contrast, during sustained submaximal contraction, signal frequency decreased with progressively increased amplitude. In fact, the response of increased sEMG amplitude to sustained sub-maximal exercise has been consistently found (Arendt-Nielsen *et al.*, 1989; Bigland-Ritchie, Cafarelli, *et al.*, 1986; Taylor & Gandevia, 2008).

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Focusing solely upon sEMG amplitude, the maximal response is characterised by decreasing force and sEMG, whilst the submaximal response involves force maintenance (or decrease) with increased sEMG. The maximal decreased response is explained by the de-recruitment of fatiguing motor units and/or reduced motor neuron output (Taylor & Gandevia, 2008). The increased submaximal response is explained by additional recruitment of active motor units and their increased firing rate (Farina, Foscu, & Merletti, 2002). This recruitment of new motor units is related to a decreased recruitment threshold as a result of muscle fatigue (Gazzoni, Farina, & Merletti, 2001). Specifically, a progressive recruitment of larger (type II) motor units occurs to compensate for de-recruitment or reduced force output of the fatigued smaller (type I) units. For example, Gazzoni *et al*. (2001) demonstrated recruitment of new motor units accompanied increased sEMG amplitude during 10 minutes of sustained 10% MVC contraction. Therefore, progressive increase in sEMG amplitude due to new motor recruitment during sustained submaximal contractions implies peripheral muscle fatigue (Moritani *et al.*, 1986; Sogaard *et al.*, 2006). Adam & De Luca (2005) provided further evidence of the modulation of motor unit recruitment and firing rates during sub-maximal contractions. Using fine wire EMG electrodes inserted into the muscle to isolate single motor unit, they demonstrated a decrease in motor unit firing accompanied by an increase in Pt, during the first part of a sustained 20% MVC. In contrast, towards the end of the contraction when fatigue was significant, Pt was reduced whilst motor unit firing increased. These findings were explained as modulations in recruitment threshold, in response to initial potentiation followed by fatigue (Adam & De Luca, 2005).

Less research has been conducted into dynamic exercise, partly due to the methodological issues such as variability of the sEMG signal with position and time, known as non-stationarity (Farina, Merletti, *et al.*, 2004). The research to date suggests that the sEMG

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responses to dynamic contractions may differ to the isometric condition (Kay *et al.*, 2000; Linnamo, Bottas, & Komi, 2000). Kay *et al.* (2000) compared the sEMG response during 100 s of sustained maximal isometric versus maximal dynamic concentric knee extensions. They found force progressively decreased during isometric and concentric conditions, reducing to 30% and 58% of initial values respectively. In contrast, the sEMG amplitude progressively reduced during the isometric contraction, to 38% of the initial value, but was maintained during the dynamic condition. Kay *et al.* (2000) suggested ischemia would be greater at the end of the maximal isometric trial compared to the dynamic condition. This would result in metabolite accumulation and biochemical changes (*e.g.* altered K^+ concentration) that lead to reduced action potential propagation and altered Ca^{2+} release and re-uptake (Cairns & Dulhunty, 1995; Fitts, 1994). However, these peripheral changes also result in afferent signalling (type III & IV) inducing spinal inhibition of motor neuron firing. This inhibition may explain the reduced sEMG amplitude during the isometric task. In contrast, the concentric condition results in greater force decrement after 100 s of maximal exercise due to the greater demand to maintain contraction force compared to isometric exercise (Kay *et al.*, 2000). However, less ischemia results in less metabolite related afferent inhibition. Direct evidence of this explanation was not provided.

Hassani *et al.* (2006) compared the sEMG amplitude response between 25 repetitions of maximal and 60 repetitions of submaximal (60%) dynamic knee extensions. During the maximal trial, sEMG first increased and then decreased. In comparison, during the submaximal trial there was continual sEMG increase throughout. This suggests reduced motor unit activation following maximal dynamic exercise, contradicting Kay *et al.* (2000), and increased activation during sustained submaximal dynamic exercise. Furthermore, studies have demonstrated the relationship between the intensity of dynamic exercise and the rate of sEMG amplitude increase, and suggested additional motor unit recruitment is

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exercise intensity dependent (Dias da Silva & Goncalves, 2006). The latter investigation used the root mean square (RMS) processing method to calculate sEMG amplitude. RMS is a mathematical method used in electrical engineering to calculate the average electrical voltage varying over time and reflects both the frequency and amplitude of the signal. Therefore, the processed RMS value may reflect both firing rate and degree of motor unit activity and is a suitable sEMG measure for fatigue investigations (Dias da Silva & Goncalves, 2006).

Overall, this research suggests that the sub-maximal sEMG response is similar in both isometric and dynamic conditions. However, Potvin & Bent (1997) found that degree of increase during the sub-maximal dynamic exercise exceeded the increase found during isometric. This was explained by the greater force generation demand during the repeated concentric (shortening) contractions in comparison to isometric contractions, resulting in greater additional motor unit recruitment (Enoka & Fuglevand, 2001). Potvin & Bent (1997) concluded that dynamic sEMG information is similar in nature to that obtained from isometric contractions, even if the two conditions may differ in terms of the degree of change and/or measurement accuracy. Therefore, both isometric and dynamic submaximal contractions show an increased sEMG response. During dynamic maximal contractions the findings discussed are equivocal, but any reductions found are likely to be less than isometric maximal exercise.

1.1.2.1 Applied research investigating dynamic sEMG fatigue

Applied research into dynamic sEMG fatigue responses has been conducted with cycling and resistance exercises. For example, Kay *et al.* (2001) monitored the sEMG amplitude and power outputs during maximal 60 s sprints interspersed at 10-minute intervals, within 60 minutes of sustained cycling. The results showed that both sEMG amplitude and power

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reduced relative to sprint one as the exercise progressed. A potential issue with the study was that subjects were not well-trained cyclists, and so pacing skills may have confounded the findings. However, the finding was later supported by a study of fatiguing repetitive cycle sprints (Racinais *et al.*, 2007). The decreased sEMG amplitude during endurance exercise represents reduced voluntary drive resulting in reduced motor unit recruitment (Noakes *et al.*, 2001). This suggests central fatigue occurs during sustained or repetitive high intensity cycle exercise and supports the findings that endurance exercise is associated with central fatigue, as discussed in section 1.1.1.

In contrast to the endurance cycling responses, research investigating the sEMG response of dynamic resistance exercise shows a similar response to the submaximal dynamic contractions summarised above. This is to be expected. For example, Pincivero, Aldworth, Dickerson, Petry, & Shultz (2000) examined repetitive of bodyweight lunge exercise performed to failure and found the sEMG amplitude (RMS) of the vastus lateralis muscle increased to 150% relative to repetition one. The same increasing response pattern was also shown during the knee extension exercise (Pincivero *et al.*, 2006). As explained above, increased sEMG during repeated submaximal contractions implies local muscle fatigue that is compensated with additional motor unit recruitment. This supports the findings from the NM assessment models discussed in 1.1.1 that suggests peripheral muscle fatigue occurs following submaximal dynamic exercise (Behm *et al.*, 2002; Klass *et al.*, 2004).

More recent research, specific to this thesis, has examined the sEMG response to a series of sets of resistance exercise. Gonzalez-Izal *et al.* (2010) studied sEMG amplitude of the *vastus lateralis* muscle and power output (concentric phase) during five sets x 10 repetitions of moderate load leg press exercise, with 2 minutes rest. This is a typical high

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volume strength or hypertrophy training protocol (see section 1.2.1). The findings showed power decreased and sEMG increased within each set. The increase sEMG is again interpreted as representing compensatory recruitment indicative of peripheral fatigue processes (Sogaard *et al.,* 2006). Similarly, Ahtiainen & Hakkinen (2009) found sEMG amplitude increased during four sets of 12RM knee extensions and Bosco, Colli, Bonomi, von Duvillard, & Viru (2000) found increased sEMG amplitude with maintained power during leg press following strength training protocols. Finally, Smilios *et al.* (2010) found increased sEMG amplitude with decreased power during four sets x 20 repetitions of barbell squat exercise, using 50% of maximum load. As above, the findings showed, suggesting resistance exercise fatigue (reduced power) is accompanied with compensatory additional motor unit recruitment. Therefore, it would seem that the sEMG response typical of sustained submaximal exercise occurs during sets of hypertrophy type resistance exercise.

This research suggests that the combined analysis of power and sEMG during dynamic barbell exercises is a useful research method specific to the aims of this thesis. Firstly, it enables direct assessment of the specific exercise performance. This may compliment information gained from pre versus post NM assessments, such as MVC, and may reveal recruitment strategies in response to fatigue. Furthermore, it allows NM responses to be monitored throughout resistance exercise sessions, from the first to last set in a series. The resistance exercise session research to date suggests peripheral muscle fatigue is occurring during sets of strength training. However, this has focused upon sessions designed to improve hypertrophy, where peripheral fatigue may be necessary to promote protein muscle synthesis (Holm *et al*., 2008). It would be insightful to employ the same methods to investigate the NM response to sessions designed to improve maximum strength and power, where adaptation is associated with the central nervous system

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1.1.2.2 Methodological issues of sEMG

In the research discussed above, the explanations given for changes in sEMG amplitude are in terms of NM recruitment levels. This is because sEMG amplitude is considered to represent motor unit activity (Adam & De Luca, 2005; Farina, Foscu, *et al.*, 2002). However, there are significant methodological limitations that influence how much the sEMG signal can be taken to represent recruitment (Enoka & Fuglevand, 2001; Farina, Merletti, *et al.*, 2004). These limitations are of particular concern during dynamic contractions. The first issue relates to geometry effects influencing the electrical signal recorded at the surface of the muscle. For example, as the muscle lengthens and shortens it changes shape relative to the electrode placement upon the skin surface. This change results in increased signal variability, including shifts in the motor units detected (Farina, Merletti, Nazzaro, & Caruso, 2001). In addition, surface electrodes are biased to detecting superficial motor units, which in turn may also bias detection towards the larger (type II) units (Farina, Merletti, *et al.*, 2004). Other influences comprise the degree of subcutaneous tissue and the detection system itself. It is therefore essential that sEMG investigations follow well-established methodologies (De Luca, 1997) and in particular use the most appropriate placement of electrodes for each muscle (Farina *et al.*, 2001).

The raw sEMG signal must be processed into an amplitude value. For example the RMS method explained above. However, a significant degree of signal cancellation is possible during the processing. This means that there is a mismatch between the motor neuron output in terms of firing rates and recruitment and the measured sEMG amplitude (Farina, Merletti, *et al.*, 2004). This is reinforced by the lack of linearity in the force to sEMG relationship (Alkner et al., 2000), implying the measurable sEMG amplitude does not reflect the increases in recruitment number and firing rate required to increase force. The disassociation between force and sEMG amplitude also occurs during fatigue (Bigland-

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Ritchie, Johansson, Lippold, & Woods, 1983; Fuglevand & Keen, 2003). In other words, changes sEMG amplitude may not match similar changes in force. For example, during repeated submaximal contractions fatigue may lead to increased motor unit recruitment to compensate for reduced force generation in currently active motor units, whilst firing rates may concurrently decrease due to afferent signalling (Enoka & Stuart, 1992) and possible attempts to optimise NM recruitment (Marsden, Meadows, & Merton, 1983). Therefore, the processed sEMG amplitude may increase or be maintained during contractions where firing rates decrease with fatigue. Consequently, sEMG amplitude changes do not proportionately represent changes in descending neural drive or motor neuron firing rates.

Furthermore, changes in sEMG amplitude that is detected on the skin may reflect peripheral events (Fitts, 1994; K. Masuda, Masuda, Sadovama, Inaki, & Katsuta, 1999). In fact it is difficult to differentiate physiological changes at a central, NMJ or peripheral level (Merletti, Rainoldi, & Farina, 2004). Fitts (1994) describes changes that occur in pre- and post-synaptic excitability, which result in reduced motor unit firing rates. Muscle membrane action potential propagation may also be reduced due to H^+ increases leading to K^+ concentration flux (Jones, 1996). In this way action potential propagation changes are a result of other fatigue processes, not the cause of fatigue (Dimitrova & Dimitrov, 2003). As previously stated in 1.1.1, one method of overcoming this issue is to include peripheral measures that represent NM transmission, such as M-wave, alongside sEMG variables (Perrey *et al.*, 2010). M-wave amplitude is considered to represent the level of NMJ activity (Dimitrova & Dimitrov, 2003) and therefore can be used as a reference to distinguish between central and NMJ changes (Perrey *et al.*, 2010). Finally, intrinsic variation, such as hydration status and sweat rates, along with possible geometric and procedural issues means that the processed sEMG amplitude value needs to be normalised against at reference contraction. This allows comparisons between experimental

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conditions, trial days and individuals (De Luca, 1997). A variety of methodologies have been used in the literature as reference contractions (Burden, 2010). However, one commonly used method is the peak sEMG amplitude value obtained during the MVC force assessment, which is recommended by the SENIAM project (Hermens *et al.*, 1999). Normalisation from MVC reference contractions has been criticised, due to possible variability. However, it has been shown to be reliable if subjects are able to consistently produce a maximal voluntary effort (Burden, 2010).

In summary, the sEMG signal is correlated with neural drive and motor neuron firing rates, but not directly representative of these processes (Gandevia, 2001; Milner-Brown & Miller, 1986). In addition peripherally located changes may influence the detected sEMG signal (K. Masuda *et al.*, 1999; Zwarts & Arendt-Nielsen, 1988). In general, this discussion has demonstrated that the key issue for sEMG researchers is to understand what the sEMG signal variables represent, in physiological terms. This is because no single sEMG variable is directly related to a single physiological process. Instead, variables represent many possible processes, possibly occurring simultaneously (Merletti *et al.*, 2004).

The reliability of quadriceps sEMG amplitude measurements during isometric knee extension exercise has been shown to be good, with between-trial coefficient of variation of 7% (Rainoldi, Bullck-Saxton, Cavarette, & Hogan, 2001). Acceptable levels of reliability of sEMG amplitude (RMS) has also been reported during dynamic knee extension exercise (Larsson, Karlsson, Eriksson, & Gerdle, 2003), with between-trial interclass correlation coefficients of $r = 0.82$ for RMS amplitude of the *vastus lateralis* muscle. A similar level of reliability ($r > 0.80$) was also found during sets of 10 repetitions of knee extensions (Larsson *et al.*, 1999).

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Given this reliability, sEMG analysis during strength training sessions may be of benefit as it provides an indication of the muscle activation during exercise in real time. This means, independently and alongside any force or power changes, NM recruiment processes associated with sEMG can be monitored from the onset of exercise. If fatigue is considered as a process and not an end point (Enoka & Duchateau, 2008; Gandevia, 2001), then measurement of observable changes throughout exercise is useful, despite unresolved methodological limitations (Farina, 2006). The sEMG amplitude can indirectly show peripheral fatigue through the elevation of motor unit recruitment compensating for decreased force-generating capacity in the muscle. Central fatigue, by contrast, is shown by a decrease of the sEMG signal, with methodological issues aside, such as signal cancellation, altered firing rates with fatigue and possible NMJ changes.

1.1.2.3 Muscle Fibre Conduction Velocity

The previous discussion focused upon sEMG amplitude findings, however sEMG frequency and conduction velocity variables have also been used to investigate recruitment strategies (Farina, Foscu, *et al.*, 2002). These variables have helped to identify the timing and mechanisms of fatigue (Arendt-Nielsen *et al.*, 1989; Kay *et al.*, 2001; Macdonald, Farina, & Marcora, 2008). Frequency variables are understood to represent muscle fibre conduction velocity (MFCV). This is because the speed of action propagation influences the sEMG power spectrum. As such, the median frequency of the power spectrum of the raw sEMG signal, and other variables, have been used to monitor fatigue and recruitment strategy processes (Dimitrova & Dimitrov, 2003). During both prolonged maximal and sub-maximal isometric contractions, the frequency variables have been shown to reduce (Arendt-Nielsen *et al.*, 1989; Taylor & Gandevia, 2008). Therefore, reduced frequency of the sEMG signal during sustained contractions suggests reduced MFCV due to peripheral fatigue processes.

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It is assumed that there is a linear relationship between frequency and MFCV, but this has been shown to be limited to static, non-fatiguing contractions (Farina, 2006). Specifically, the processing of frequency variables from the sEMG signal during dynamic contractions has methodological limitations (Enoka & Fuglevand, 2001; Farina, 2006). This is due to changes in muscle lengths influencing the shape of the action potentials, thereby influencing signal frequency independent of motor unit firing rates. In addition, variations in the location of the active motor units, such as the depth in relation to the surface electrode, known as volume conductor effects, may also change the spectral properties of the detected signal (Farina, 2006; Farina, Foscu, *et al.*, 2002). In addition, fatigue processes influence frequency variables, independent of changes in MFCV. This is because fatigue leads to changes in the number and position of active motor units, which in turn influences frequency variables. Consequently, signal frequency variables and MFCV have shown to be poorly correlated during fatiguing contractions (Farina, Fattorini, Felici, & Filligoi, 2002; Farina, Foscu, *et al.*, 2002; Farina, Merletti, *et al.*, 2004; Lowery, Nolan, & O'Malley, 2002). As it is now possible to measure MFCV directly, some researchers have used this, rather than frequency variable to investigate fatigue (A. M. Hunter *et al.*, 2009; Macdonald *et al.*, 2008).

MFCV is proposed to represent the net balance between motor unit recruitment and local fatigue processes (Arendt-Nielsen *et al.*, 1989). The relationship between MFCV and motor unit recruitment comes from original research that showed increased conduction velocity with larger muscle fibre diameter in isolated frog muscle (Hakansson, 1956). This is because larger fibres with greater conduction volume allow for faster action potential propagation. The relationship between fibre type and muscle fibre diameter in human muscle has been established (Brooke & Engel, 1969), showing fast twitch fibres possess higher MFCV in human subjects. This was supported by a study demonstrating a linear

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correlation (r = 0.87) between motor unit evoked twitch force and MFCV values (Andreassen & Arendt-Nielsen, 1987). From this Andreassen & Arendt-Nielsen (1987) concluded that MFCV was related to the Hanneman 'size principle', where larger MFCV values would represent overall greater type II motor unit recruitment.

The rationale for MFCV representing local fatigue processes comes from the fact that the peripheral events that can influence NM transmission and action potential propagation, which affects the measured MFCV (Fitts, 1994; K. Masuda *et al.*, 1999). For example, it has been shown that increased H^+ and reduced muscle pH directly reduced measured MFCV (Brody, Pollock, Roy, De Luca, & Celli, 1991). Reduced pH results in imbalances in Na^+ and K^+ concentrations in the extracellular membrane, which impairs action potential propagation (Fitts, 1994). Arendt-Nielsen *et al.* (1989) found MFCV increased during prolonged 10% MVC isometric contraction, whereas MFCV decreased during 40% MVC contraction. They interpreted the difference by suggesting that additional larger motor units were recruited during the low force task without significant fatigue effects. However, the higher force task resulted in greater fatigue and any possible MFCV increase due to additional recruitment was negated by the metabolite accumulation reducing the MFCV (Arendt-Nielsen *et al.*, 1989). These findings have been repeated, with low force tasks showing increased MFCV (Gazzoni *et al.*, 2001) and high force tasks resulting in reduced MFCV (K. Masuda *et al.*, 1999). In this way, MFCV can be used as a measure of peripheral fatigue, providing supplementary information to sEMG amplitude.

MFCV has been investigated in dynamic exercise. For example, MFCV has been shown to relate to cycle pedal power (Farina, Ferguson, Macaluso, & De Vito, 2007) and pedal force (Farina, Macaluso, Ferguson, & De Vito, 2004). MFCV has also been shown to increase in proportion to the force during dynamic leg press exercise (Pozzo *et al.*, 2004). These

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findings suggest that in non-fatiguing dynamic contractions, MFCV represents the overall mean motor unit recruitment, similar to the isometric condition. Larger MFCV therefore represents greater proportion of larger motor unit recruitment. However, it is difficult to distinguish between increased firing rate and increased large (type II) motor unit recruitment, as firing rate influences the MFCV detected (Farina, Foscu, *et al.*, 2002).

The reliability of MFCV from the quadriceps muscle has been reported in the literature. Repeated trials of isometric knee extension exercise, reported within-subject coefficient of variation of 4.6-7.9% and between-trial intraclass correlation coefficient of r = 0.82 (Rainoldi *et al.*, 2001). In addition, repeated cycling trials found inter-trial coefficient of variation of 5.5% and intraclass correlation coefficient of r = 0.78 (Macdonald *et al.*, 2008).

In summary, MFCV could be an informative variable to investigate recruitment strategies and fatigue during resistance exercise training, however, the sensitivity of changes in MFCV under fatigue conditions during dynamic exercise has been questioned (K. Masuda *et al.*, 1999). Other limitations exist in terms of methodology and interpretation of MFCV results (Enoka & Fuglevand, 2001). Motor units have also been shown to have varied MFCV values within and between fibre types (Enoka & Fuglevand, 2001; Troni, Cantello, & Rainero, 1983) and changing muscle lengths also influence MFCV estimates (Kossev, Gantchev, Gydikov, Gerasimenko, & Christown, 1992; MacIsaac, Parker, Scott, Englehart, & Duffley, 2001). This means analysis of MFCV during dynamic contractions is problematic. Despite these issues, the inclusion of MFCV measurements in the present thesis during investigations of maximum strength and power training sessions may yield novel and interesting findings, as there is no previous research specifically addressing this.

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This discussion of sEMG amplitude and MFCV variables leads to the following conclusions. The amplitude response is specific to exercise conditions and varies between maximal versus submaximal and isometric versus dynamic contractions. Interestingly, sEMG amplitude can be used to monitor muscle activity during resistance exercise sessions, with research to date showing increased sEMG amplitude within sets of repetitions, suggesting peripheral fatigue in the muscle is compensated for with increased motor unit recruitment. The real-time monitoring of fatigue during strength and power training may be valuable, as it provides a specific measurement in the dynamic condition from the onset of exercise. The increased muscle activation implied by increase sEMG amplitude may indicate stimulus for NM adaptation. For example, greater muscle fibre recruitment has been associated with enhanced cross sectional area and force adaptations (Takarada, Takazawa, *et al.*, 2000). Specific limitations exist for sEMG amplitude data, and researchers must be circumspect in the interpretation of results. Limitations also exist in the measurement of MFCV, however it may provide further information of fatigue and recruitment strategies during dynamic strength training.

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1.1.3 Neuromuscular fatigue and potentiation responses to strength training

1.1.3.1 Neuromuscular response to strength training

Section 1.1.1 summarised the NM fatigue research, including studies of isometric and dynamic tasks as well as applied exercise investigations, such as cycling or resistance exercises. The discussion described some studies that investigated resistance exercises. These investigations typically comprised single bouts of repetitions performed to fatigue (Behm *et al.*, 2002). These single bouts of dynamic exercise are distinct to entire structured resistance exercise sessions. The latter comprise a series of sets of repetitions, usually involving one or more exercises. The sets are interspersed with rest intervals, which enables repeat performance of load levels across the sets (see *Appendix 1)*. Structured sessions are designed with specific volume, intensity and exercise speed to target specific physical outcomes: Sessions of high intensity (above 80% maximum load) and low repetitions (two to six) are performed to develop maximum strength. Moderate intensity sessions (50-80% of maximum) with higher repetitions (six to 12) are performed to develop hypertrophy (ASCM, 2009; Crewther *et al.*, 2005). Finally, high velocity exercises, with a range of loads and low repetitions, are performed to develop power (McBride *et al.*, 2002; Moss *et al.*, 1997; Wilson *et al.*, 1993).

In the following discussion, and throughout the thesis, the terms maximum strength, hypertrophy and power describe the type of training session performed. They are not used as physiological terms *per se*, and do not necessarily refer to the NM response to the resistance exercise. See section 1.2.1 for more detailed discussion of the three types of resistance exercise session.

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Most of the research to date has assessed the NM response to sessions using MVC force assessment, along with sEMG amplitude during the MVC test (Hakkinen, 1993, 1994, 1995). In these studies, the training loads were reported as the repetition maximum (RM), for example 10RM. This is useful as it describes both volume of exercise per set, *e.g.* 10 repetitions, and the intensity of the load, *e.g.* the weight that can be lifted only 10 times with maximum effort. The 1RM load represents the maximum load for a given exercise, and can be seen as the dynamic exercise equivalent of the MVC force value. For example, 10RM is approximately 75% of 1RM, depending upon the exercise (Shimano *et al.*, 2006).

Hakkinen (1993) studied the response to a high intensity maximum strength training session comprising of 20 sets x 1RM machine squat, with three minutes rest between sets. In order to maintain 1RM intensity, the load was reduced as the session progressed. The MVC and sEMG measurements were taken prior to the session and were compared to assessments taken immediately following the completion of the 20th set. The findings showed a 20% decrease in MVC with reduced sEMG amplitude during the MVC. The authors concluded a reduced neural drive contributed to this loss of force, based upon the reduced sEMG value, however no M-wave or Pt measurements were made that directly assessed possible changes at the NMJ or in the muscle's contractile properties. A separate investigation, using similar methodology analysed fatigue following a hypertrophy training session of 10 sets x 10RM machine squats (Hakkinen, 1994). This protocol led to a greater reduction in post exercise MVC compared to the 20 x 1RM protocol. This is likely to be due to the higher volume of exercise compared to the previous study. Interestingly, greater fatigue was shown in male subjects compared to females, as MVC reduced by 47% and 29% respectively. This was related to significantly greater post session blood lactate concentration (15.0 v 6.0 mmol.L^{-1}), suggesting male subjects performed more muscular work resulting in greater contractile dysfunction (Hakkinen, 1994).

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Ahtiainen, Pakarinen, Kraemer, & Hakkinen (2003) also showed reduced MVC and sEMG during MVC following a strenuous hypertrophy training session. Subjects performed a series of eight sets of multi-joint leg extension exercises using 12RM load. However, during each set more than 12 repetitions were performed as assistance was provided until exhaustion occurred. Post session MVC force reduced by 60%. This was most likely due to the very demanding protocol, which represents advanced hypertrophy training. The reduction in sEMG amplitude during MVC was taken as evidence of central fatigue. In contrast, Ahtiainen & Hakkinen (2009) showed a significant reduction (30%) in MVC force following four sets x 12RM knee extensions, with no change in sEMG amplitude. This suggested no central fatigue occurred following this lower volume training protocol.

In general, the above research suggests both the volume and intensity of the session type influences the degree and nature of acute NM fatigue. This is not surprising as fatigue responses have been shown to be specific to volume or duration of exercises, for example cycle sprints versus endurance (Billaut & Basset, 2007; Racinais *et al.*, 2007). However, it is difficult to draw conclusions regarding the relative contribution of peripheral or central fatigue with the limited NM assessment battery used. As previously discussed, reductions in sEMG amplitude, without M-wave measurements should not be interpreted as reduced motor unit activation, as sarcolemma transmission can also influence the sEMG signal (Perrey *et al.,* 2010). It is also possible that the reduced sEMG found was due to the timing of the MVC assessment immediately post exercise in the studies above. This is because central fatigue and sEMG responses have been found to recovery quickly following maximal contractions (Taylor & Gandevia, 2008). A more comprehensive methodology with specific variables representing the peripheral and central sites, using Pt and VA% or CAR may provide more detailed information (Kent-Braun, 1999).

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Other research into acute strength training responses using similar methodologies has compared fatigue following different training types (Linnamo *et al.*, 1998; Linnamo, Pakarinen, Komi, Kraemer, & Hakkinen, 2005). For example, a session comprising five sets x 10RM leg press was compared with a session comprising five sets x 10 repetitions at 40% 10RM explosive leg press. The isometric leg press MVC force measured immediately post the final set was reduced by 23% post heavy and 11% post explosive session for males and by 19% post heavy and 12% post explosive for females (Linnamo *et al.*, 2005). This data suggested that specific responses to different session types exist, however this is confounded the differences in total work between protocols.

To overcome this limitation, McCaulley *et al.* (2009) conducted a comparative study comprising different sessions with matched volume defined by total work. The protocols were hypertrophy (4 sets x 10 repetitions of squats at 75% 1RM load), maximum strength (11 x 3 squats at 90% 1RM load) and power (8 x 6 vertical jumps at body mass load). Isometric squat MVC force and rate of force development (RFD), along with sEMG during the MVC test were measured before and immediately post sessions. MVC and RFD decreased by 17% and 26%, 23% and 29%, and 7% and 3% following strength, hypertrophy and power sessions respectively. The sEMG amplitude during MVC reduced post maximum strength, but not hypertrophy and power sessions. This data suggests there was limited fatigue following the power session, whilst significant fatigue occurred post maximum strength and hypertrophy. The change in sEMG post strength session suggested that some central fatigue contributed to the decrease in MVC in this session only. Interestingly, the maximum strength session appeared to influence RFD more than the other sessions, as RFD was not fully recovered 24 hours post, in contrast to hypertrophy and power. McCaulley *et al.* (2009) argued the reduced RFD was further evidence of central changes following the strength session, although acknowledging no direct

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measurements were made. However, this finding may have functional significance for sports performance and emphasises the utility of including RFD assessment in fatigue research (Thorlund *et al.*, 2008).

The study by McCaulley *et al.* (2009) represents one of the better studies of acute NM fatigue following strength and power training as the session protocols were highly realistic in terms of the type, intensity and volume of exercise. In particular, subjects performed free weight barbell and jumping exercises as opposed to machine based ones. This is important as elite athletes commonly use free-weight resistance exercises. See *Appendix 1* for details of exercises prescribed by elite strength and conditioning coaches. Greater training benefit in functional movement has been shown from multi-joint resistance exercises compared to isolated joint movements (Augustsson, Esko, Thomee, & Svantesson, 1998). This is because of greater mechanical and intra-muscular similarities between these exercises and the sport specific movements (Behm, 1995). Furthermore, free-weight barbell squat exercise has been shown to produce greater muscle activation levels (43% greater sEMG amplitude) in comparison to machine squat exercise of matched intensity (Schwanbeck *et al.,* 2009). This is likely to be due to increased NM demand in stabilisation and control of posture during free-weight versus supported movements (Maluf & Enoka, 2005). Research has shown that differences in supported versus unsupported type of loading, influences both rate of fatigue and motor unit recruitment (Mottram *et al.*, 2005). Therefore investigations of free weight resistance exercises are important, as NM responses may vary due to the specific exercise task. McCauley *et al.* (2009) concluded further NM investigations into maximum strength and power training was warranted, particularly regarding the contribution of peripheral and central fatigue. The use of VA% or CAR and Pt variables alongside MVC and sEMG amplitude measures would achieve this robustly.

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In summary, the NM fatigue research into entire structured resistance exercise sessions has demonstrated fatigue, in terms of reduced force generation capacity and associated decreased muscle activation. However, the latter was based solely upon sEMG measurements and the investigations above did not use a comprehensive NM assessment model, as discussed in section 1.1.1 (Kent-Braun, 1999; Perrey *et al.*, 2010; Sogaard *et al.*, 2006). A comprehensive assessment battery has been applied to single sets of resistance exercise (Behm *et al.*, 2002) as previously discussed, but not entire structured sessions.

The only session study found to use a comprehensive NM assessment model compared the changes in VA%, MVC and Pt between different sessions of elbow flexion exercise (Tran *et al.*, 2006). The sessions were classed as either high or low volume and short or long time under tension (TUT). All three sessions resulted in reduced MVC force and Pt, with no change in VA%, providing evidence of peripheral fatigue. Interestingly, the high volume and longer TUT session resulted in greatest fatigue, in line with the findings above for greater volume hypertrophy training sessions. However, TUT was more influential than volume on fatigue, with the low volume but longer TUT session resulting in greater fatigue than the high volume, short TUT protocol. It is possible that the prolonged tension elicits greater contractile stress, resulting in greater peripheral fatigue. It would be interesting to investigate the influence upon NM response to repetitions of different duration as well as load. Variation in duration would directly influence the impulse of a resistance exercise, where impulse is defined as the product of force and time. Impulse has been shown to vary between different resistance exercise sessions and may influence adaptation and fatigue (Cronin & Crewther, 2004). Specific investigation of the influence of TUT and impulse on NM response between different free weight exercises and different types of training session would be of interest.

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The type of methodology used by Tran *et al*. (2006) may provide interesting findings about the nature and mechanisms of fatigue following elite strength and power training sessions. However a possible limitation of this NM assessment battery being applied to strength training is the lack of specificity of the MVC assessment to dynamic exercise. During investigations of sustained single joint isometric or dynamic contractions the MVC force test directly represents fatigue. However, in applied exercise research, MVC merely represents the change in the force generating capacity in one of the prime mover muscles following the exercise bout. In contrast, it is power as a dynamic measurement of performance that directly represents fatigue during resistance exercise (Cairns *et al.*, 2005). This is because the power output of the exercise is considered a meaningful representation of resistance exercise performance combining both the force and the velocity of the movement (Bosco *et al.*, 2000). Therefore, an alternative approach to strength and power research may include sEMG and power monitoring during the performance of the resistance exercises, similar to the methods used during cycling (Billaut & Basset, 2007; Kay *et al.*, 2001). Power measurements during resistance exercise may be made using position transducer devices, which allow power to be estimated from displacement data. For example, power may be monitored during repetitions of squat or leg press exercise using this method (Bosco *et al.*, 2000; Smilios *et al.*, 2010). As discussed in section 1.1.2.2, these studies showed that reductions in power were accompanied by increased sEMG, suggesting peripheral muscle fatigue and compensatory neural drive. Smilios *et al.* (2010) argued that further barbell exercise research would be insightful, as real-time monitoring of power and sEMG are direct and specific measures of the fatigue process. Therefore, just as studies of isometric tasks directly measured force to monitor fatigue (Bigland-Ritchie, Cafarelli, *et al.*, 1986; Bigland-Ritchie, Furbush, *et al.*, 1986; Merton, 1954), research of resistance exercise training sessions should monitor the power performance of each set and repetition.

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McCaulley *et al.* (2009) also suggested the addition of jump assessments may enhance assessment of NM function pre- and post- resistance exercise. This is because jumps require high velocity of muscle contraction and may identify the specific type of fatigue following dynamic exercise. Jump performance is also a functional measure that represents the type of rapid movement important for sports performance, and so is useful as a fatigue indicator for coaches and athletes. However, it is worth noting that force and power measures during jumping maybe more sensitive to fatigue than jump performance itself (Cormack, 2008). Both jump performance and jump related variables have been shown to be reliable measures when assessed using either force platforms (Cormack, Newton, McGuigan, & Doyle, 2008) or position transducers (Sheppard, Cormack, Taylor, McGuigan, & Newton, 2008; Young, MacDonald, Heggen, & Fitzpatrick, 1997). Therefore, a jump assessment is practicable and of specific interest to elite athletes.

Investigations of NM fatigue of applied exercise have made NM assessment measurements either immediately or a number of minutes following the exercise bout. For example, studies of endurance cycling exercise (Bentley *et al.*, 2000) and power type resistance exercise involving barbell squats (Chui *et al.*, 2004) assessed NM function 10 minutes following the end of the exercise. In contrast, the studies of resistance exercises sessions discussed above made NM assessments immediately post the final set of repetitions (Bosco *et al.*, 2000; Hakkinen, 1993, 1994). However, this may be a methodological weakness, due to the nature of resistance exercise sessions. As explained, structured sessions comprise a series of sets of repetitions, with rest intervals between sets. Interestingly, exhaustion at the end of structured maximum strength and power sessions is not necessarily the objective and may not occur. Assessments made immediately following the completion of the session will bias the findings to the fatigue accrued in the final set. For example, a session of 10 sets x 10 reps with the assessment occurring immediately

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after the 10th set, means that this test becomes the equivalent of an 11th repetition of the 10th set. Therefore, NM assessments made a few minutes post the completion of the session may be more informative, allowing the impact of the whole training session to be assessed. This has practically significance for elite athletes who may need to perform other types of training following strength and power sessions. In this case, knowledge of the fatigue going into the next activity is of more interest than the immediate fatigue following the final set of resistance exercise itself.

The timing of post exercise assessment is complicated by the fact that recovery times may vary between different measures of fatigue. For example, central fatigue (VA%) has been shown to recover at a faster rate than peripheral fatigue (Pt) (Sogaard *et al.*, 2006). Although Klass *et al*. (2004) showed no difference in MVC and sEMG amplitude measured immediately or five minutes following fatiguing dynamic plantar flexion exercise. In addition, measured Pt values may reflect both concurrent post-activation potentiation and fatigue at the time of the test (Fowles & Green, 2003; Gandevia, 2001). It has been shown that post-activation potentiation may reduce with time, and so Pt assessments made a few minutes rather than immediately following contractions are more likely to reflect fatigue (Fowles & Green, 2003; Morana & Perrey, 2009). This may be important for understanding the relative contributions of central and peripheral mechanisms following resistance exercise sessions.

The issue of post exercise NM assessment timing supports the potential benefit of using real time monitoring of power and sEMG during investigations of resistance exercise sessions. As a result, the fatigue (measured by the change in power) is automatically known throughout each exercise set. Furthermore, the sEMG measurement provides information of the NM response to the exercise set. Therefore, there is no need to

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immediately assess force generation capacity using an MVC to determine the degree of fatigue post the final exercise set. Consequently, post-session MVC and other NM assessments may be taken a few minutes post the completion of the final set, thereby better reflecting the overall fatigue resulting from the session. The combination of real time monitoring during the resistance exercise sets and NM assessments made following the entire session also overcomes the potential issue that force generation capacity and exercise performance are not necessarily related (Chiu *et al.*, 2004). This ensures that both specific exercises changes and general physiological responses are appropriately assessed.

A further limitation of the NM fatigue research into strength training is that the majority of investigations have been hypertrophy type training sessions (McCaulley *et al.*, 2009). These are distinct in terms of volume, intensity and speed of exercise to maximum strength and power training sessions (see section 1.2.1). Importantly, not all athletes train using primarily hypertrophy type sessions. Typically, a mix of speeds and loadings and volumes of session are utilised (Schmidtbleicher, 1992). In addition, the repetition maximum (RM) method used to control load levels between subjects differs to how elite athletes actually perform training sessions. This is because RM, by definition, is the maximal load that can be achieved for a given number of repetitions. As a result of maintaining RM intensity during the investigations, subjects performed sessions involving progressively reduced loads. In contrast, during elite strength and power training the load is usually progressed upwards or maintained at a target load throughout the series of sets (*see Appendix 1)*.

Therefore, the resistance exercise sessions researched to date, in terms of both training type and loading methods, are not representative of typical methods employed by elite athletes. Understanding the degree and nature of fatigue following elite strength and power sessions is important to help plan the volume and timing of sessions within a weekly training

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programme involving other training activities along with resistance exercise. The optimisation of performance results from ensuring all training activities result in positive adaptation. Coaches may use information gleaned from investigations of specific elite training methods to avoid accumulation of excessive fatigue across the week and also limit fatigue that may interact between consecutive training sessions. Specifically, being able to make informed decisions between different exercises, session types and volumes may facilitate training planning.

In summary, some interesting research has been conducted into the degree of force generation capacity change following applied resistance exercise training sessions. The research has predominately assessed high volume hypertrophy type training. Little research has been conducted utilising a comprehensive NM assessment model (Tran *et al.*, 2006) or comprising realistic elite training sessions, in terms of exercise, load and volume (McCaulley *et al.*, 2009). In addition, only a few studies have analysed barbell exercise training in real time (Smilios *et al.*, 2010). No study to date has combined all three methodological approaches into one fully comprehensive investigation of elite strength and power training methods. This will be one of the key aims of the present thesis.

1.1.3.2 Post Activation Potentiation

The previous section aimed to establish a rationale for further NM fatigue research into resistance exercise sessions, specifically elite athlete training practices. However to complete the discussion of neuromuscular research relevant to the present thesis a further section exploring post activation potentiation (PAP) is thought to be relevant. This is due to the fact that PAP has been shown to relate to NM performance measures following strength and power training.

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PAP has been researched in both the laboratory and strength training setting. In fact, there is more applied resistance exercise research investigating PAP, than NM fatigue. PAP is the improved muscle force generation capacity as a result of its contractile history, normally termed a conditioning contraction (Hamada, Sale, MacDougall, & Tarnopolsky, 2000; Hodgson, Docherty, & Robbins, 2005). Two types of PAP have been studies, involving different mechanisms at different sites in the NM system, twitch and reflex potentiation (Hodgson *et al.*, 2005).

Twitch potentiation refers to increased evoked force (Pt) following MVC's (Gossen & Sale, 2000; Hamada, Sale, & Macdougall, 2000) or tetanic stimuli (O'Leary, Hope, & Sale, 1997), see figure 1.2. High frequency stimulation of the whole muscle (duration 5 - 10 s) has been shown to elicit increased twitch response immediately following the stimulus. This is known as post-tetanic potentiation and is similar to the PAP following MVC's of 10 s duration (O'Leary *et al.*, 1997; Vandervoort *et al.*, 1983). Twitch potentiation is related to the phosphorylation of the myosin light chains leading to improvements in E-C coupling due to enhanced cross-bridge interactions. In brief, more force results from a similar Ca^{2+} concentration (Babault, Maffiuletti, & Pousson, 2008; Fowles & Green, 2003; Vandervoort *et al.*, 1983).

Figure 1.2. Schematic of potentiation of Pt following 7 s of high frequency tetanic stimulation, adapted from (O'Leary et al., 1997).

The figure shows evoked twitch (Pt) on the right following the tetanic stimulation is greater than pre-stimulation, on the left. A similar response is shown following 10 s MVC's (Vandervoort *et al.*, 1983).

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Evoked twitch assessment (Pt) is a common method for demonstrating the potentiated twitch response. However, Fowles & Green (2003) suggested that the rate of twitch development (dF/dt) from the evoked assessment is the best measure of potentiation, where dF/dt is defined as the Pt divided by the time to reach Pt. Research has shown dF/dt may be less influenced by low frequency fatigue mechanisms (Fowles & Green, 2003; O'Leary *et al.*, 1997). For example, during repetitive contractions, Pt and dF/dt increase early in the exercise, whilst only Pt decreases as exercise progresses and fatigue accumulates. (Fowles & Green, 2003; Morana & Perrey, 2009). This suggests Pt represents the balance of potentiation and fatigue. In addition, the increased dF/dt is sustained for longer following a conditioning contraction in comparison to Pt (O'Leary *et al.,* 1997).

Studies measuring changes in Pt have shown that PAP is influenced by the proportion of fast twitch muscle (Babault *et al.*, 2008; Hamada, Sale, MacDougall, *et al.*, 2000), and the subjects' training history (Hamada, Sale, & Macdougall, 2000; Morana & Perrey, 2009). It would seem that stronger individuals with greater type II muscle fibres are more likely to benefit from a PAP response. This related to the phosphorylation mechanism having a greater effect in type II muscle fibres (Hamada, Sale, MacDougall, *et al.*, 2000).

Reflex potentiation is the increased motor unit response to an evoked afferent (type Ia) volley. This is usually shown as the increased H-reflex measured by the sEMG signal following sub-maximal stimulation. The increased H-reflex represents improved NM transmission in the spinal cord, specifically greater motor neuron activation resulting from afferent signals (Hodgson *et al.*, 2005). The H-reflex is best expressed relative to the M-wave response, as this represents the excitability of action potential propagation at the post-synaptic NMJ, which also influences possible change in measured H-reflex. Figure 1.3A shows an example of the maximum H-reflex evoked in the quadriceps muscle.

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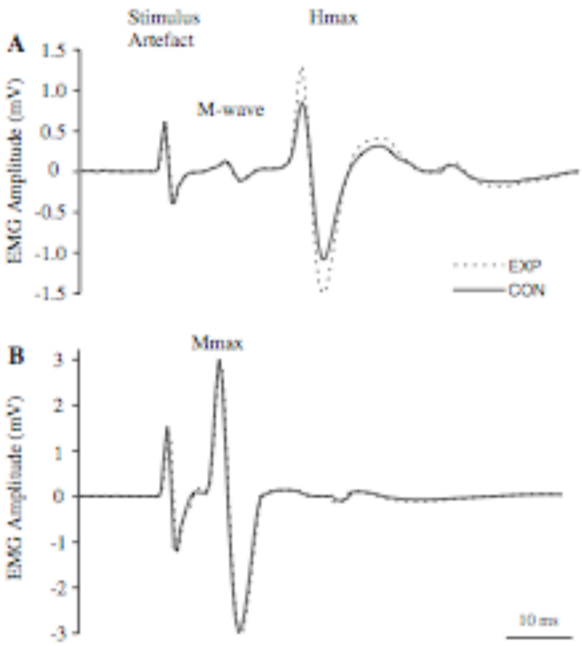

Figure 1.3. A) Maximum H-reflex measured by sEMG in response to sub-maximal twitch stimulation, and B) Maximum M-wave signal, adapted from Folland, Wakamatsu, & Fimland (2008).

The top figure A shows a dotted line (EXP) in comparison to the solid line at rest (CON), demonstrating the increased H-reflex 5 minutes post a 10 s MVC conditioning contraction. Bottom figure B shows there is no difference between M-wave at rest and post MVC. Therefore the H reflex, relative to M-wave was increased, implying greater afferent reflex motor unit activation.

Research has shown changes in the M-wave and H-reflex following voluntary conditioning contractions (Gullich & Schmidtbleicher, 1996; Trimble & Harp, 1998). Typically, this increase occurs a few minutes following the contraction. For example, following eights x 10 repetitions of maximal plantar flexion repetitions, H-reflex was initially depressed and then potentiated after four minutes and up to 10 minutes post exercise (Trimble & Harp, 1998). The M-wave response was shown to be stable throughout. An increased H-reflex response was also shown following 10 s MVC's and related to an increased voluntary rate of force development during jumping (Gullich & Schmidtbleicher, 1996). This suggests that the enhanced reflex responses may result in improved neuromuscular performance, which has potential value for the athlete to optimise performance. However, the research to date is equivocal on whether the improved H-reflex, and also Pt, responses are realised in voluntary muscle actions.

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Voluntary potentiation and PAP were compared by assessing Pt response with maximal velocity knee extensions performed at a range of isokinetic force levels immediately following a conditioning contraction of 10 s of knee extension isometric MVC's (Gossen & Sale, 2000). Whilst Pt was increased, there was no improvement in force-velocity characteristics. These findings were supported by a study that found both reflex potentiation (increased H-reflex) and twitch potentiation (increased Pt) of the quadriceps occurred following 10 s of knee extension isometric MVC. However, no improvement in dynamic knee extension RFD was found (Folland *et al.*, 2008). This was despite concurrent reflex and twitch potentiation at the time of the voluntary dynamic test. Furthermore, there is limited evidence that isometric MVC or dynamic peak force is potentiated by conditioning contractions (Tillin & Bishop, 2009). This may relate to the phosphorylation mechanism of PAP, which suggests Ca^{2+} saturation during high frequency (e.g. MVC) contractions may negate possible PAP effects (Vandenboom *et al.*, 1995).

In contrast to these findings, enhanced jump performance has been shown following MVC's (French, Kraemer, & Cooke, 2003; Gullich & Schmidtbleicher, 1996), with a concomitant change in the force time properties of the jump. This possibly suggests stiffness or co-ordination changes occurred, similar to that shown in elite rugby players (Comyns, Harrison, Hennessy, & Jensen, 2007; Comyns, Harrison, Hennessy, & Jensen, 2006). This may relate to changes in muscle fibre pennation angles following MVC's influencing force transmission to the tendon (Mahlfeld, Franke, & Awiszus, 2004). Therefore, potentiation during voluntary contractions may be specific to the type of exercise assessed. A review of literature would suggest that vertical jumps are most common voluntary exercise where a potentiation response is shown (Tillin & Bishop, 2009), including following heavy squat exercise as the conditioning contraction (Weber, Brown, Coburn, & Zinder, 2008; Young, Jenner, & Griffiths, 1998).

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Investigations of voluntary PAP investigations also show many factors that may influence the degree or existence of a PAP response. The most important factors seem to be subject related in terms of strength, training history, gender and age (Tillin & Bishop, 2009). The enhancements in jump performance following MVC conditioning contractions discussed above were found in groups of elite track and field athletes (French *et al.*, 2003; Gullich & Schmidtbleicher, 1996). In addition, Chiu *et al.* (2004) showed only strong subjects demonstrated improved RFD following a whole session of explosive squats exercise at 70% of 1RM squat. This was related to the fact that the strong group had higher proportions of fast twitch fibres, as shown by muscle biopsy techniques. The influence of strength was also shown in a separate investigation into jumping performance following a dynamic squat session (Ruben, Molinari, Bibbee, Childress, Harman, *et al.*, 2010).

In contrast, Mangus *et al.* (2006) found there was a range of potentiation responses following squat training across a group of subjects, and that the variation was not related to strength levels. This suggests the there is a highly individual response to session intensity and volume that influences whether PAP occurs. This may be best explained by the fact that an observable PAP response is dependent upon the net balance between fatigue and potentiation (Fowles & Green, 2003; Morana & Perrey, 2009). The stimulus required for PAP is relative to each individual, as is the dose of exercise that results in fatigue. Therefore, specific sessions may or may not result in PAP. The benefit for strong subjects may simply be they are less likely to suffer fatigue following the exercise. This could also explain why endurance athletes benefit from PAP (Hamada, Sale, & Macdougall, 2000).

Of more practical significance for elite athletes and coaches and of greater relevance for this thesis, is whether potentiation results from whole sessions of resistance exercise. This was examined by (Duthie, Young, & Aitken, 2002) using a session protocol comprising

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high load squats and light load squat jumps. Three sets of each exercise was performed, either alternating heavy then light, or with three light sets followed three heavy sets. No effect was found for the alternating load session on light load jump performance. However, Duthie *et al.* (2002) suggested the mixed strength levels within the group may have influenced the results, as in fact some subjects did show a gain in jump performance. Further limitations of the study was that session volume was small relative to typical strength sessions and light load jump performance was the only outcome measure of PAP.

The relevance of PAP for the current thesis is twofold. Firstly, potentiation may be possible following resistance exercise sessions. However, this may depend upon the type of test exercise, subjects and volume and intensity of resistance exercises performed. For example, vertical jumps may be more likely to show voluntary potentiation than force assessments. Specifically, there is less information on whether whole sessions can elicit the PAP response, compared to conditioning contractions or small doses of strength exercise. Further studies of whole sessions may reveal whether potentiation can occur or not. The second reason is the co-existence of potentiation and fatigue processes and the potential impact upon understanding the acute fatigue response. Investigations into fatigue cannot be distinct from PAP, as the two processes are likely to be ongoing throughout sessions. Potentiation may offset fatigue at certain points during and following a resistance exercises sessions and the timings of Pt assessment may be influenced by both factors simultaneously (Fowles & Green, 2003; Morana & Perrey, 2009).

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1.2 Strength and Power training methods

Resistance exercise training is commonly split into three distinct training categories, maximum strength, hypertrophy, and power. The terms maximum strength and hypertrophy refer to the training objective of the resistance exercise session. In other words, the terms define resistance training to improve maximum strength or hypertrophy. The term power may be confusing as it reflects the performance of the exercise and the aim of the session. The present thesis refers to maximum strength, hypertrophy and power as terms to describe the type of resistance exercise session with respect to the training aim.

The American College of Sports Medicine 2009 position stand described maximum strength training comprising sets of 1-6RM, hypertrophy training as sets of 6-12RM and power training as sets of 0-60% 1RM (lower body) or 30-60% 1RM (upper body) performed explosively (ASCM, 2009). 1RM is the maximum load that can be lifted and is the dynamic resistance exercise equivalent of 100% MVC force. As load, or intensity, is reduced, it is possible to perform a greater number of repetitions. For example, 10RM is equal to approximately 75% 1RM load (Shimano *et al.*, 2006). In a comprehensive review Crewther *et al*. (2005) distinguished between three kinds of traditional strength programmes. The first involves loads greater than 85% 1RM and results in predominantly neural adaptations. The second consists of loads around 70% 1RM and results mainly in a hypertrophy adaptation, or increased muscle cross sectional area. The third type of resistance training is termed power and involves loads of 30-50% 1RM that are performed explosively (Crewther *et al.*, 2005). More recently, Cormie, McGuigan, & Newton (2010a) defined maximum strength training by the load range of 75-90% 1RM versus power training by 0-30% 1RM. The variation in load used to define power training is related to whether exercise includes body mass, such as squat, or involves external resistance only, such as machine weights. This is because RM loads typically refer to the

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weight of the resistance machine or barbell. However, the exercise may involve the system mass, defined as the sum of the athletes' body mass (or part of it) and the external load. Therefore, power exercises such as jump involve body mass and therefore need lower additional load in comparison to upper body movements, where only the barbell is moved.

In summary, there are three types of resistance exercise training goal each comprising sessions with specific intensity, volume and speed of movement. However, the discussion below argues that the lines between the categories are not entirely clear. For simplicity the discussion below views maximum strength and hypertrophy as specific categories distinguished by load and repetition, whilst power training is seen as involving high velocity execution of a possible range of relatively light loads.

1.2.1 Maximum strength and hypertrophy training methods

Strength can be developed through an increased muscle cross sectional area (CSA) and increased ability to activate and co-ordinate motor units. In other words, adaptation occurs across the whole neuromuscular system. The stimulus-tension theory states that high muscle forces and contraction times elicited during resistance exercises result in muscle protein breakdown, which then stimulates re-synthesis (McDonagh & Davies, 1984). This theory explains how muscle adapts following training with high loads. In fact, muscle protein synthesis over many hours following resistance exercise has been shown to exceed muscle protein breakdown occurring as a result of the training session (Kumar, Atherton, Smith, & Rennie, 2009). In addition, high muscle forces require high motor unit activation, which leads to neural adaptations (Aagaard, 2003; Sale, 1988). For example, following a 14-week leg training programme comprising four to five sets x 3-10RM loads of multiple exercise, there was increased MVC and RFD post training, along with increased sEMG during MVC (Aagaard *et al.*, 2002a). The increase in sEMG suggests the

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training enhanced motor unit activation leading to increased strength. In a separate study comprising 14 weeks of 6-10RM resistance training, Aagaard *et al.* (2000) found that a previous deficit in sEMG activity during high force contractions was improved. From this they concluded the training protocol had resulted in reduced neural inhibition, suggesting spinal mechanisms such as afferent signals from Golgi organs and muscle spindle may have changed (Aagaard *et al.*, 2000). In a follow up study, Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen (2002b) provided direct evidence of neural changes at a spinal level by demonstrating increased H-reflex amplitude following a similar 14-week training protocol. Interestingly, Jensen, Marstrand, & Nielsen (2005) demonstrated increased strength levels and sEMG amplitude were independent of motor cortex activity changes in comparison to skill training, using trans-cranial magnetic stimulation of specific cortical areas. Indirectly this supports spinal level neural mechanisms are involved in strength adaptation (Duchateau, Semmler, & Enoka, 2006).

Load intensity is a primary factor for maximum strength adaptation, but there is also evidence that exercise execution is important. Specifically, the intention to perform the resistance exercise as quickly as possible, even if high loads prevent fast movement, will maximise the neural drive to the muscles (Ives & Shelley, 2003). Thus, despite maximum strength exercises being slow, high muscle activation is more influential on the neural adaptation than the external kinematics of the movement performance (Behm & Sale, 1993a, 1993b). These findings suggest that is it difficult to distinguish maximum strength from power type training, which also involves fast execution. The only difference may be that as loads are relatively light during power training, high external movement speeds are achieved.

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Hypertrophy training is similar to maximum strength, but typically involves greater volume and so fast movement execution is perhaps not as critical. Load level must be sufficiently high otherwise the stimulus tension adaptation mechanism will not occur. However, a greater volume of training seems to result in superior hypertrophy gains. For example, a study comparing the eight week adaptation to 3-5RM versus 9-11RM versus >20RM training schemes found the higher load protocols resulted in significantly greater muscle mass gain, as shown by muscle biopsy techniques, compared to the >20RM protocol (Campos *et al.*, 2002). This suggests a threshold intensity exists, to ensure sufficient stimulus-tension to facilitate protein breakdown and re-synthesis. This is supported by recent findings showing muscle protein synthesis post resistance exercise is optimised when loads between 60% and 90% of 1RM are used (Kumar, Selby, *et al.*, 2009). Therefore, high volume of resistance training alone will not optimise the hypertrophy response, without sufficient load intensity (Holm *et al.*, 2008).

The literature supports both higher volume and relatively high load for maximising hypertrophy (ASCM, 2009; Crewther, Cronin, & Keogh, 2006). The reason for this appears to be that fatigue is important for the hypertrophy response. This is because fatigue stimulates the myogenic pathways, metabolic, and endocrine systems that influence adaptation (Crewther, Cronin, *et al.*, 2006; Crewther, Keogh, Cronin, & Cook, 2006; Schoenfeld, 2010). This is in contrast to maximum strength protocols, where fatigue is unnecessary for neural adaptation (Gabriel, Kamen, & Frost, 2006). For example, Kraemer *et al.* (1990) found that five sets x 10RM, with a one minute versus three minute rest interval between sets resulted in greater human growth hormone response, suggesting increased metabolic demand facilitates endocrine response, which may in turn promote muscle adaptation (Takarada, Nakamura, *et al.*, 2000). However, this benefit was not directly established in this research. Another benefit of high volume training is that higher

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repetition number may result in a greater NM stimulus. As discussed above in section 1.1.2.2, performing dynamic resistance exercise until fatigue leads to increased sEMG amplitude to compensate for peripheral muscle fatigue. This indicates greater motor unit recruitment, and may provide a possible NM stimulus for strength adaptation (Ahtiainen & Hakkinen, 2009; Gonzalez-Izal *et al.*, 2010; Pincivero *et al.*, 2006).

In summary, maximum strength and hypertrophy differ and can be viewed as sub-categories of strength training. Both require heavy loading, but maximum strength adaptation is optimised with higher loads of 2-6RM, where both muscle force and neuromuscular activation can be optimised. Hypertrophy training is typically performed with loads of 8-12RM, where a balance between muscle force and work can be achieved.

1.2.2 Power type resistance training

Power is mechanically different to force, as it is derived from the product of force and velocity. It is therefore time dependent and by definition must involve dynamic movement. In contrast, force can be expressed dynamically or statically. It has been shown that maximum strength and power are distinct physical qualities (Nedeljkovic, Mirkov, Markovic, & Jaric, 2009) and consequently training sessions to specifically develop power are distinct. Power training exercises are characterised by fast or explosive movements, sometimes termed ballistic. Importantly, exercises performed explosively have been shown to be beneficial for athletic performance (Behm, 1995; Wilson *et al.*, 1993). This may be due to adaptations resulting from the additional stretch-shorten cycle force contributions and/or increased periods of acceleration during the concentric phases of the exercises (R. U. Newton *et al.*, 1997).

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Evidence suggests that the neural adaptation resulting from power training is similar to that from maximum strength in terms of increased motor unit activation. However, it is also related to increased RFD and early onset motor unit recruitment (Aagaard, 2003). Van Cutsem *et al.* (1998) provided direct evidence of this in a study investigating sEMG and force changes following explosive resistance exercise at 30% 1RM load (10 sets x 10 reps dorsi flexion). Following 12 weeks of this training maximum force, RFD and sEMG amplitude during the first 50 ms of force generation had all increased. Van Cutsem *et al.* (1998) suggested increased motor unit discharge rates explained the RFD improvement, which was specifically related to the load and execution of the training exercise.

Other research has shown that eccentric force generation capacity increases as a result of dynamic explosive training, such as squat jumping (Cormie, McGuigan, & Newton, 2010). Good evidence exists that power training (defined as 0-30% 1RM of explosive exercise) result in significant changes in power and jump performance (Cormie *et al.*, 2010b). These eccentric force and power adaptations may be specific to movements involving stretch-shortening cycles, such as jumping. In addition, improved muscle contraction velocity may result from this kind of training (Malisoux, Francaux, Nielens, & Theisen, 2006). These adaptations are important for athletes who must perform rapid movements to succeed in sports.

It is also possible that the adaptations to power training are velocity specific (Behm & Sale, 1993b). High speed low force movements were not improved following a high force low speed resistance training programme (Aagaard, Simonsen, Bangsbo, & Klausen, 1996). Therefore, to optimise performance in athletic movements such as running and jumping, fast movement speeds with loads specific to one's own body mass may be more useful (Wilson *et al.*, 1993). This specific adaptation has been demonstrated in a comparative

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study of heavy versus light load squat jumps, where only the light load training group increased power outputs following eight weeks of training (McBride *et al.*, 2002). In contrast, Moss *et al.* (1997) showed that maximum force and power both increased following heavy and light load training. However, the key difference in this study was that subjects performed all repetitions as explosively as possible, regardless of load level. This is sometimes termed maximal intent training. This finding has been supported by studies that have also required subjects to exert maximal intent, regardless of loading levels. For example, Blazevich & Jenkins (2002) showed no difference in response to heavy versus light load resistance training both performed with maximal intent, performed in conjunction with sprint training. Similar to maximum strength training discussed above, it may be that to ensure power adaptation, exercise execution must consist of high internal muscle contraction velocity (Behm & Sale, 1993a). The external movement speed and power outputs may be secondary factors to force generation (Cronin & Sleivert, 2005)

Analogous to maximum strength and hypertrophy, it may be clearer to define power training in two distinct exercise types. The first involves the performance of explosive or powerful concentric movements, such as the squat jump or power clean. The second involves rapid performance of the eccentric concentric movement cycle, such as speed squats or vertical jumps (Stone, Stone, & Lamont, 2004). Cronin & Crewther (2004) discussed how this latter type, which typically involved body mass or light loads can result in increased eccentric force production. Examples of this training can be found in elite athletes strength programmes (R. U. Newton *et al.*, 1999) (see also *Appendix 1*).

The relevance of this discussion to the present thesis is to establish the distinctions between training methods in order to justify specific investigations and comparative studies. In summary, maximum strength, hypertrophy and power training differ in terms of intensity,

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volume and execution, with some overlapping features, such as the range of loads and intention to perform exercises explosively (Cormie, McCaulley, & McBride, 2007). Furthermore, this thesis aims to analyse strength and power training specifically used by elite athletes. Wilson *et al.* (1993) found greater speed and agility performance improvements following 10 weeks of explosive light load training versus heavy training. Therefore, power may be as important as the maximum strength and hypertrophy categories for certain athletes. The NM fatigue research to date has mostly studied hypertrophy schemes. Therefore the focus of this thesis is to investigate maximum strength and power training sessions.

1.2.3 Hormonal response to resistance exercise

Resistance exercise has been defined and distinct types of training described in relation to the aims of this thesis. In addition, the hormonal response to resistance exercise requires a brief examination as it may influence the acute NM response. Firstly, this is because strength training has been shown to influence hormonal response, possibly more significantly than other exercise modes, such as endurance training (Tremblay, Copeland, & Van Helder, 2004). Secondly, acute hormonal responses, in terms of increased testosterone levels for example, may in turn lead to acute changes in NM performance (Crewther, Cook, Cardinale, Weatherby, & Lowe, 2011). In fact, testosterone is the most likely hormone to have possible influence upon the NM system based upon it fast acting effects upon brain activity (Smith, Jones, & Wilson, 2002) and muscle cell Ca^{2+} concentrations (Estrada, Espinosa, Muller, & Jaimovich, 2003). Therefore, testosterone will be the focus of the following discussion.

Previous research has focused upon determining which type of training session elicits the greatest testosterone response (*e.g.* Ahtiainen *et al.*, 2003; Kraemer *et al.*, 1990). The

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consensus of the literature suggests that hypertrophy type sessions lead to greater testosterone responses than maximum strength sessions (Crewther, Keogh, *et al.*, 2006). For example, Hakkinen & Pakarinen (1993) found that a session comprising 10 sets x 10 repetitions of squat at 70% 1RM resulted in a greater testosterone response than the session comprising 20 sets x 1RM. In addition, explosive or power type sessions have also been shown to increase testosterone, similar to the hypertrophy sessions (Pullinen, Mero, MacDonald, Pakarinen, & Komi, 1998). The reasons for these different training mode responses are not well explained in the literature (Crewther, Keogh, *et al.*, 2006) and may involve changes in sympathetic nervous system (Pullinen *et al.*, 1998) and/or the metabolic demands in response to exercise (Tremblay, Copeland, & Van Helder, 2004).

To further understand the mechanisms behind these differences, research has investigated the role of training session volume on endocrine response. Crewther, Cronin, Keogh, & Cook (2008) provide evidence of the importance of volume load upon testosterone and cortisol response. They compared hormonal responses following three sessions of equal duration. The hypertrophy session comprised 10 sets x 10 repetitions squat and had the highest training volume. The maximum strength session comprised 6 x 4 squats and the power session of 8 x 6 jumps and both sessions were matched in terms of training volume. They showed a peak testosterone response, relative to pre-session levels, occurred 15 minutes post the hypertrophy session and remained elevated for 60 minutes. Cortisol levels were also elevated post hypertrophy training. In contrast, there was a flat testosterone response following power and maximum strength sessions relative to baseline, along with reduced cortisol levels. This study concluded session volume is the primary factor influencing acute hormonal response. This suggests that the previous findings that show power type training result in high testosterone responses may be a result of training volume and not training type. This research was followed by a different study comparing

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hormonal response to different sessions that were matched for mechanical work (McCaulley *et al.*, 2009). The results showed that the hypertrophy session elicited the greatest testosterone and cortisol response, in comparison to maximum strength and power sessions. As session volume, defined by mechanical work was equal, the differences between sessions was related to the significantly higher lactate concentrations post hypertrophy. This suggests metabolic work is a mechanism which influences post resistance exercise hormonal response (McCaulley *et al.*, 2009) and is possibly related to the influence of lactate on testosterone secretion (Lu *et al.*, 1997).

Research has focused upon hormonal responses following resistance exercise based upon the view that it is important for chronic adaptation of strength and muscle hypertrophy (Kraemer *et al.*, 1990; McCall, Byrnes, Fleck, Dickinson, & Kraemer, 1999; Ronnestad, Nygaard, & Raastad, 2011). It is well established that Testosterone influences skeletal muscle synthesis. Therefore, if greater exercise induced testosterone is exposed to the muscle, the possibility of increased muscle cell receptor interactions occurs, thereby increasing the muscle protein response (Ahtiainen et al., 2003). However, the contention that hormonal responses are critical to the strength adaptation process has been recently challenged (West *et al.*, 2010; West & Phillips, 2010). These studies found no difference in strength and muscle cross sectional area (hypertrophy) when strictly controlled elbow flexor training was performed in either high versus low hormone (testosterone) conditions. This suggests that the intrinsic stimulus of the resistance exercise itself is more important than the post-exercise testosterone levels (West *et al*., 2010).

Of greater relevance to the present thesis is the question of whether short-term testosterone responses following resistance exercise sessions may influence the acute NM performance. Crewther *et al.* (2011) discussed emerging evidence of hormonal changes affecting the

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muscle cell, motor cortex and behaviour; processes that in turn can affect exercise performance. Indirectly, the relationship between testosterone levels and NM performance has been shown in jump and sprint performance in elite athletes (Bosco, Tihanyi, & Viru, 1996; Crewther, Lowe, Weatherby, Gill, & Keogh, 2009). However, this may simply reflect individual variation between athletes, and not any acute influence on performance. Stronger evidence of the short-term influence of testosterone levels upon NM performance comes from studies which show correlations between jump and weightlifting performances and daily resting testosterone levels (Cardinale & Stone, 2006; Crewther & Christian, 2010). This short term effect is perhaps explained by testosterone increasing excitability of the NMJ via biochemical pathways (Blanco, Popper, & Micevych, 1997) and greater Ca^{2+} release in the muscle, improving contractile function (Estrada *et al.*, 2003). Therefore, the acute hormonal responses to resistance exercise may affect the assessment of NM function during and post training. In addition, subject training history (Ahtiainen, Pakarinen, Kraemer, & Hakkinen, 2004: Tremblay, 2004) and time of day (Bird & Tarpenning, 2004) may mediate or amplify these acute responses. It is also possible that the endocrine response to the same training sessions is highly varied between individuals, even in homogenous elite athlete groups (Beaven, Gill, & Cook, 2008). It would seem therefore, that monitoring the hormone response to strength and power training may better inform investigations into NM fatigue.

In summary, the majority of evidence suggests that hypertrophy or high volume training schemes will lead to superior hormonal responses, however responses may by highly subject specific. There is emerging evidence that acute testosterone levels influences NM performance and therefore it is important to understand what effect these levels may have on NM fatigue investigations. Whilst many studies have analysed fatigue and hormone responses to resistance exercise concurrently (Ahtiainen *et al.*, 2003; Linnamo *et al.*, 2005;

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McCaulley *et al.*, 2009), few have attempted to relate the post training hormone and NM responses (Bosco *et al.*, 2000).

1.2.4 Kinetic & Kinematic investigations of resistance training

The final section of this review introduces the research concerning the mechanical assessment of strength and power exercises, as real time monitoring of exercises is one of the aims of this thesis. Power measurement has dominated the mechanical research into resistance exercise (Garhammer, 1993). Power is the product of force and velocity of a movement. During resistance exercise it is typically derived from measurements of the displacement of the load and ground reaction force (Cormie, McBride, & McCaulley, 2007). Other mechanical variables have been used to describe resistance exercise, such as impulse, total work and time under tension (TUT) (Crewther *et al.*, 2005). Impulse is the amount of force applied over the time of an exercise and is derived from the integral of force as a function of time. Total work represents the total mechanical energy expressed during an exercise as is derived as the integral of power as a function of time. TUT is used to describe the duration of the exercise, which is perhaps confusing as tension is not dependent upon movement.

The power measured during a resistance exercise varies in relation to the load lifted. In fact there is an inverse relationship between load and power, measured during the concentric phases of strength and power exercises (Rahmani, Viale, Dalleau, & Lacour, 2001). This is based upon the well-established force-velocity relationship (A. V. Hill, 1938). As muscle force increases, the velocity of a shortening (concentric) muscle contraction reduces. This is because of the structural nature of muscle force generation; increased contraction velocity reduces the time available for the myosin and actin binding mechanism to occur. Theoretically, isolated muscle actions optimise power at 30% of peak

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force. As the load of a dynamic resistance exercise is related to force, power is also optimised at sub-maximal loads.

Typically, the purpose of measuring power has been to determine the resistance exercise load level that optimises power adaptation (Crewther *et al.*, 2005). Research has commonly focussed upon bench press and squat movements. Power is derived from the displacement of the load measured directly from the movement of the barbell (Alemany *et al.*, 2005; Baker, 2001; Cormie, McBride, & McCaulley, 2008; Hori, Newton, Nosaka, & McGuigan, 2006; Newton & Dugan, 2002). For lower body movements, such as the squat, the correct methodology for estimating power involves calculations summing the mass of the barbell and the athlete. This is termed system mass load (defined above) and is important otherwise the correct force values are not measured. It is also recommended that force be measured directly from force plates and independently of the movement speed (Cormie, Deane, & McBride, 2007; Hori *et al.*, 2007; Hori *et al.*, 2006). This research has led to the understanding that bodyweight jumps, without external load, optimises the power of lower body exercises (Cormie *et al.*, 2008; Cormie *et al.*, 2010a).

In a comprehensive review of the mechanical aspects of strength training research, Crewther *et al.* (2005) discussed how kinematic and kinetic descriptions of exercises are common, but not whole training sessions. This is analogous to the gap in NM fatigue investigations of entire strength and power sessions in contrast to discrete exercise bouts. Crewther *et al.* (2005) suggest that information regarding whole training sessions may be more informative than single exercise descriptions for understanding the stimulus and fatigue response to training. For example, Cronin & Crewther (2003) showed light load training performed with greater volume led to greater overall session force and impulse compared to heavy load performed for fewer repetitions. Cronin & Crewther (2004) provided a wide mechanical description of strength and power sessions by comparing

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force, impulse, TUT and power during squat training at three different loading levels. They showed session differences on all variables, with greater power during the light load session and greater impulse during the heaviest session, despite matched session volume. Therefore, power may not be the only mechanical variable of significance (Crewther *et al.*, 2005). In particular, impulse may be insightful, as it is the product of force and time, and so may reflect the stimulus-tension mechanism of adaptation (Cronin & Crewther, 2004). Thus, impulse may distinguish between exercises in terms of adaptation and fatigue responses. However few studies have reported the impulse variable to date (Crewther *et al.*, 2005; Cronin & Crewther, 2003). Total work is another useful measure to describe entire training sessions as this may also be related to the adaptation response (Kramer *et al.*, 1997; Munn, Herbert, Hancock, & Gandevia, 2005). In addition, total work may better represent session training volume compared to the traditional volume load measure (McBride *et al.*, 2009).

Mechanic descriptions of resistance exercise have been reported using machine-based or free-weight exercises of upper and lower body movements. Elite athletes tend to use free-weight exercises, such as Olympic-style lifts, in preference to machine-based exercises. Freely moving resistance exercises have greater mechanical and intra-muscular similarity to athletic movements (Behm, 1995). Specifically, mechanical similarities between jumping and weightlifting exercises have been demonstrated (e.g. squat, clean, jerk) (Canavan, Garret, & Armstrong, 1996; Garhammer & Gregor, 1992). The jump and weightlifting movements involve dynamic extensions of the ankle, knee and hip joints. Coaches refer to this as 'triple extension'. Furthermore the joint angles at which peak joint forces are applied during jumping and weightlifting are similar (Garhammer & Gregor, 1992). Related to this, studies have shown greater training benefits, as measured by jump performance, were shown following free-weight versus machine-based resistance exercise

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training (Augustsson *et al.*, 1998). In addition, greater weightlifting performance is associated with greater jump and sprint performance, Hori *et al.* (2008) suggesting shared force and/or power generation characteristics between sprinting, jumping and weightlifting. Consequently, free-weight exercises are considered essential by strength and conditioning coaches (Stone *et al.*, 2000). *Appendix 1* summarises a survey of strength & conditioning coaches working with the UK's elite athletes and showing the majority of training programmes comprise barbell exercises. Therefore, investigations of free-weight exercises are of specific interest. Prime mover muscles, such as the quadriceps contribute significantly to the force generation of leg extension in free-weight exercises such as squat, with high muscle activation and knee joint moments (Escamilla *et al.*, 1998; Wretenberg, Feng, & Arborelius, 1996). This suggests the quadriceps may incur NM responses following resistance exercise sessions and make a suitable test muscle group of multi-joint free-weight exercises.

In summary, power has dominated the mechanical research of strength and power exercise and good methodologies have been established. However, total work and impulse merit further investigation and mechanical analysis of entire sessions would be informative, over and above single repetition descriptions (Cronin & Crewther, 2004). Therefore, the mechanical analysis of whole strength and power sessions may assist in understanding the NM fatigue response to elite strength and power training sessions.

1.3 Conclusions and Thesis aims

Fatigue has been defined as a process (Enoka & Duchateau, 2008) and measured as the change in a functional outcome, typically force, during the fatiguing task under investigation. The body of NM research has established an assessment model, comprising MVC, Pt, VA% or CAR, and sEMG as the key measurements (Kent-Braun, 1999; Klass *et*

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al., 2004; Sogaard *et al.*, 2006). The challenge to the researcher is to understand how these measurements represent physiological processes at different sites in the NM system. It is suggested that the combination of the variables enables this interpretation (Kent-Braun, 1999). However, an understanding the influence of the timing of post-exercise assessments (Fowles & Green, 2003) and in some cases the use of additional variables may be required to correctly interpret findings (Kent-Braun, 1999; Perrey *et al.*, 2010).

A pattern has emerged from the original laboratory research that suggests maximal isometric exercise induces fatigue across the whole NM system, but the central mechanisms can recovery quickly (Gandevia *et al.*, 1996). In contrast, submaximal isometric exercise of moderate duration induces fatigue mainly located in the peripheral NM system (Bigland-Ritchie, Furbush, *et al.*, 1986). Thirdly, highly prolonged and low force exercise results in both central and peripheral fatigue, which recovers slowly (Behm & St-Pierre, 1997). Following these basic findings, more applied investigations show that strenuous endurance exercise will result in both peripheral and central fatigue (Bentley *et al.*, 2000). In contrast, and in parallel to the previous isolated findings, short duration high intensity exercise, e.g. sprinting or single bouts of dynamic contractions, results in mostly peripheral fatigue (Klass *et al.*, 2004; Perrey *et al.*, 2010).

The findings from this type of NM fatigue research are interesting and suggest that a similar approach to investigating fatigue following structured resistance exercise sessions may be highly informative. In particular, further detail of the specific NM responses related to chronic adaptation may be revealed. However, few session studies have adopted this kind of comprehensive assessment model. Typically, the research conducted to date has been limited methodologically or has focused upon higher volume, lower intensity hypertrophy type sessions (Hakkinen, 1993; Linnamo *et al.*, 2005).

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Distinct types of resistance training have been defined, as maximum strength, hypertrophy and power. The focus for elite athlete performance involves sessions specifically designed to develop maximum strength and power. These sessions often comprise free-weight exercises (*e.g.* squats and Olympic-style lifts). Therefore, due to the gap in the literature, further understanding of the NM response to structured maximum strength and power sessions is warranted (McCaulley *et al.*, 2009) through the implementation of a comprehensive NM assessment model (*e.g.* Tran *et al.*, 2006). Furthermore, resistance exercise research is warranted that uses specific measurements to the dynamic condition (Cairns *et al.*, 2005). For example, recent applied research has utilised jump assessments alongside the more traditional NM test variables. This may provide more specific markers of NM recruitment and fatigue following dynamic resistance exercise.

Previously, sEMG has been used to study the NM response to exercise. An established maximal versus sub-maximal isometric response has been shown, where sEMG amplitude and frequency both reduce quickly with force during sustained maximal contractions. In contrast, sEMG amplitude progressively increases, whilst frequency or MFCV reduce, during sustained or repetitive submaximal contractions (Arendt-Nielsen *et al.*, 1989; Moritani *et al.*, 1986). This is interpreted as increased neural drive to compensate for decreased force generation capacity in the peripheral muscle. The sEMG responses to dynamic exercise have been shown to be similar but not identical to the isometric condition (Kay *et al.*, 2000). There has been some specific research into the sEMG response during sets of dynamic strength exercises. This has demonstrated that sEMG amplitude increases during sets of resistance exercise, similar to sustained sub-maximal isometric and dynamic contractions (Smilios *et al.*, 2010). Again, few studies have investigated the specific responses during structured maximum strength and power type sessions. Instead the focus has been upon hypertrophy type training. In addition, evidence from MFCV research,

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suggests this measure may provide useful information of NM recruitment strategies and peripheral fatigue during dynamic resistance exercises (K. Masuda *et al.*, 1999; Pozzo *et al.*, 2004). A key advantage of sEMG measurements is that they can be combined with power analysis in real time to monitor exercise performance (Kay *et al.*, 2001). This combination is now possible during dynamic barbell exercise (Bosco *et al.*, 2000; Smilios *et al.*, 2010). Real time monitoring also enables the research to use specific measures during dynamic exercise, as the responses may differ from the isometric condition (Cairns *et al.*, 2005). This combined assessment of the specific performance (power output) and the muscle activity (sEMG amplitude) during training, across every set and repetition, would provide information of NM recruitment to help understand possible stimulus for adaptation and fatigue response during resistance exercise. NM response investigated purely as a change from pre to post exercise bout is limited when any NM process is most likely dynamic in nature and develops from the onset of exercise and is specific to the exercise task (Enoka & Duchateau, 2008). Real time analysis also avoids issues arising from the timing of post exercise NM assessments. In conjunction with traditional NM assessment, they may provide complimentary information, helping to understand the impact of the training session.

Whilst investigating the NM fatigue response, it is important to understand the possible influence of post-activation potentiation and acute hormonal responses. Post-activation potentiation is a physiological process that occurs in parallel to fatigue (Fowles & Green, 2003; Morana & Perrey, 2009) and strength training is proven to induce potentiation under specific conditions. Investigations of NM fatigue during and following strength training sessions cannot be separated from potentiation, especially when interpreting muscle function assessments. In addition, evidence exists that acute hormonal response affects NM performance (Cardinale & Stone, 2006) and may also influence NM response.

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Kinetic and kinematic research describing strength exercise has been conducted and typically focuses upon power (Crewther *et al.*, 2005). However, research that investigates mechanical descriptors of whole training sessions may reveal both differences between training types and the mechanisms of NM response. Power provides a logical measure of fatigue ongoing during the training process, but impulse, total work and TUT may reveal further information that relate to fatigue, as they demonstrate possible links to adaptation processes (Cronin & Crewther, 2004).

One of the key aims for sports coaches is to plan optimal programmes that combine different training types, including strength, endurance, speed and technical. The reality for elite athletes is that an optimal strength training programme conducted in isolation is not necessarily the optimal programme that results in improved sports performance when combined with other training (Hakkinen, 2004). Coaches of elite athletes need to understand two factors to optimise a complex training programme. Firstly, what aspects of resistance exercise influence the degree and nature of NM fatigue? This knowledge helps plan training sessions performed during the same day or week as resistance exercise. Secondly, what are the loads, volumes and type of exercises that ensure the best stimulus for maximum strength and power adaptations? This thesis aims to further this understanding, by conducting comparative studies of the NM response resulting from structured sessions comprising different free-weight exercises and different session type. These sessions will be assessed using a traditional NM assessment battery combined with functional tests, real time sEMG and power monitoring, hormonal responses and session mechanical descriptors.

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1.3.1 Research Aims

1. To describe the neuromuscular response during and following whole sessions of resistance exercise, specifically:

– What are the differences in NM responses between different exercise sessions?

– What are the differences in NM response between maximum strength versus power type sessions?

– What is the 24-hour recovery from each type of training?

2. To investigate the nature of neuromuscular fatigue and the underlying mechanisms, specifically:

– What evidence of central and peripheral fatigue exists following maximum strength and power type sessions?

– What evidence exists relating acute hormonal response to NM fatigue?

However, prior to addressing these questions, two methodological studies must be undertaken that;

1) Establish a reliable assessment system for real time barbell exercise monitoring.
2) Investigate if MFCV measurements taken during dynamic barbell movements provide reliable and useful information in comparison to isometric contractions.

Chapter Two

Reliability of a biomechanical and sEMG analysis system during barbell squat exercise

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2. Reliability of a biomechanical and sEMG analysis system during barbell squat exercise.

2.1 Introduction

Elite athletes and clinical rehabilitation patients perform resistance exercise to promote adaptations in performance and functional movement. Specifically, free-weight, whole body and multi-joint barbell exercises, such as squat, are commonly used and recommended (Stone *et al.*, 2000). There is greater transfer to performance of barbell, in comparison to machine-based exercise (Augustsson *et al.*, 1998), due to greater kinetic and kinematic similarity between barbell and functional movements (Behm, 1995). Mechanical and muscle activity analysis during barbell resistance exercise may further understanding of the neuromuscular (NM) responses relating to the type, volume and intensity of training that optimises functional adaptation. However, in order to achieve accurate analysis of this nature, it is important to establish a reliable system that effectively measures and synchronizes the kinematic and NM variables of interest.

Power is a critical variable to measure during whole body barbell exercise, as it is the product of force and velocity, thereby representing the performance of resistance exercises (Bosco *et al.*, 2000). Power may be measured by attaching a cable linear position transducer device to the barbell to record the exercise displacement. The filtered displacement data is processed into velocity and force values, based upon the known mass of the barbell and the relevant mass of the individual, from which power is derived. This has wide usage amongst strength training researchers (Dugan, Doyle, Humphries, Hasson, & Newton, 2004), as monitoring power to enable athletes to achieve optimal exercise performance during resistance exercise is considered important to promote training

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adaption (Cronin & Sleivert, 2005; Dugan *et al.*, 2004; Wilson *et al.*, 1993). Power may also be used to monitor fatigue, defined as the progressive decline in power as a result of exercise (Cairns *et al.*, 2002). Surface Electromyography (sEMG) has been used to analyse the NM recruitment patterns during resistance exercises (Wretenberg *et al.*, 1996; Wright, Delong, & Gehlsen, 1999). Specifically, sEMG amplitude represents global motor unit recruitment, which may be influenced firing rate during maximal and sub-maximal exercise (Farina, Merletti, *et al.*, 2004; Gazzoni *et al.*, 2001). Previous research has demonstrated that the type of exercise task influences NM recruitment (Maluf & Enoka, 2005). For example, greater sEMG amplitude was found during free standing barbell versus fixed machine squats of matched intensity (Schwanbeck *et al.*, 2009). This suggests that the former will recruit more motor units, which may enhance the adaptation process (Aagaard, 2003; Sale, 1988).

Combining mechanical power and sEMG measurements together may provide useful information of the NM response with respect to barbell exercise performance. For example, Smelios *et al.* (2010) demonstrated 20% increase in quadriceps sEMG amplitude and reduced power, during a set of 12 repetitions of barbell squats. This suggests fatigue (indicated by reduced power) was associated with additional motor unit recruitment (Moritani *et al.*, 1986; Sogaard *et al.*, 2006). Unfortunately, the findings were limited, as quadriceps sEMG amplitude was processed without direct kinematic data to define the movement. Therefore, it would be more objective to be able to assess mechanical power and sEMG during barbell exercises, whilst accurately describing muscle activity (sEMG) with respect to kinematic measurements.

Recordings of sEMG synchronised with knee electrogoniometry (see figure 2.1) and a linear position transducer, could enable barbell exercises to be precisely assessed. The

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goniometry would allow for the description of the knee joint kinematics and specific identification of the start and end of movement cycles. The linear position transducer allows mechanical power estimates to be made, as explained. The practical benefit of this system is accurate sEMG analysis, without the restriction of collecting data in a fully equipped biomechanics laboratory. It is acknowledged, however, that power calculations from a single linear position transducer are limited, due to errors from acceleration and horizontal movement (Cormie, Deane, *et al*., 2007). This limitation is balanced against the benefit of collecting data in the training setting, and replaces laboratory analysis comprising digital video and force plate technologies. To enable meaningful analysis of data from this proposed analysis system described above, measurement reliability needs to be established. Therefore, the primary aim of this study is to establish during barbell squat exercise the inter-trial day reliability of knee joint angles measured using electrogoniometry, mean power estimated from linear position transducer displacement data and normalised quadriceps RMS amplitude variables.

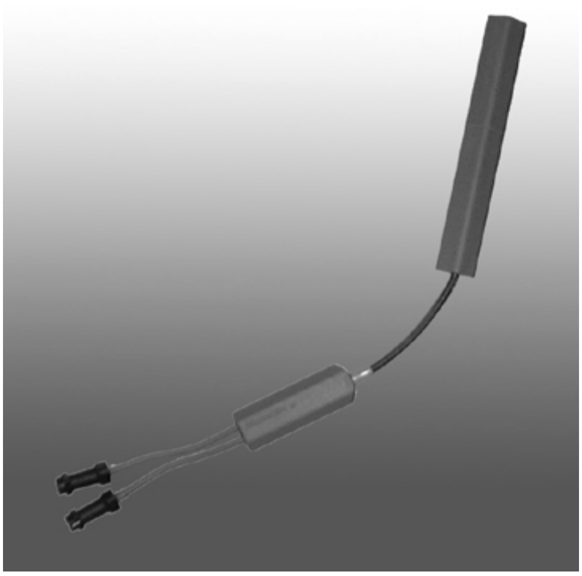

Figure 2.1. A flexible electrogoniometer (TSD130B, Biopac Systems Inc, California, USA).
Two end blocks are attached via a flexible extensible cable containing measurement sensors. The endblocks are fixed above and below the knee, aligned to the thigh and shank axis to enable knee joint angles to be obtained from the calibrated voltage output.

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Reliability of measures taken from flexible electrogoniometers suitable for this kind of application have been established (Piriyaprasarth, Morris, Winter, & Bialocerkowski, 2008). This study reported inter-tester reliability (intra-class coefficient) ranging from r = 0.6 - 0.8 and errors of up to 3.6° from 75° knee angle measurements. This analysis involved only static knee angles in direct comparison with manual goniometry. Therefore, the inter-trial reliability of electrogoniometry knee angle measurement during dynamic movement is unknown. Reliability of power estimations from a single linear position transducer attached to the barbell has been established with ballistic upper and lower body exercises. Inter-trial co-efficient of variation (CV) estimates were found between 4-10% (Alemany *et al*., 2005; Hori *et al.*, 2007; Sheppard *et al.*, 2008). Again, these reliability studies have not been conducted specifically for barbell squat exercise. The reliability of sEMG amplitude during resistance exercises and force assessments have been established. For example, quadriceps sEMG inter-trial intraclass coefficient of r = 0.82 have been found (Larsson *et al.*, 2003; Worrell, Crisp, & Larosa, 1998). However, to the researcher's knowledge, no assessment of sEMG reliability has been made specifically of the quadriceps muscle during dynamic barbell squat exercise. In the previous studies, sEMG amplitude was processed as the root mean square (RMS) of the raw sEMG signal, see figure 2.2. This technique provides a method of rectifying and smoothing the raw signal. The RMS amplitude value is normalised to a reference value obtained from a maximal voluntary contraction of the quadriceps to allow for comparison between different trial days, following recommended methods (Burden, 2010; De Luca, 1997).

As stated above, the purpose of the knee joint electrogoniometry is to provide kinematic description of the squat movement without the need for video analysis. However, it is not known if the motion of the knee joint measured by electrogoniometry represents accurately the entire multi-joint squat movement. This is because the hip and trunk may move at

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different joint angular velocities at different points in the squat movement cycle in comparison to the knee. Therefore, the secondary aim of the study is to analyse the relationship between knee joint motion and barbell displacement to determine how accurately knee joint motion represents the entire squat movement.

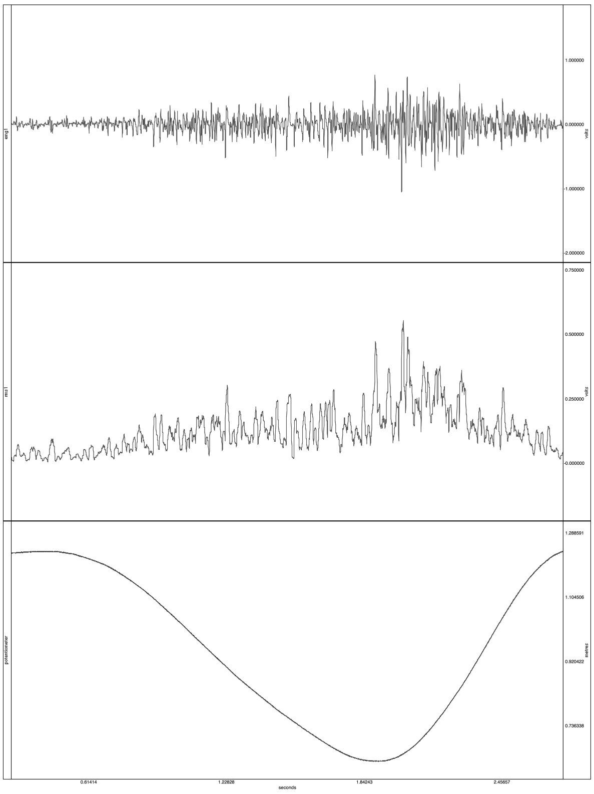

Figure 2.2. Sample software screen of raw sEMG amplitude data (top graph), processed RMS amplitude values (middle graph) and bar displacement data (bottom graph).
The displacement plot is included to illustrate the lowering and lifting of the barbell during the squat movement. Note the increase in RMS amplitude during the concentric (lifting) phase.

2.1.1 Research Questions

Firstly, what is the reliability of the three components of the proposed analysis system during the barbell squat? Specifically; a flexible electrogoniometer for measuring knee angle, a linear position transducer displacement measurement processed into mean power during the concentric phase of the squat, and the normalised RMS amplitude variable.

Secondly, what is the relationship between knee joint motion measured by the electrogoniometer and barbell displacement during barbell squat?

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2.2 Methods

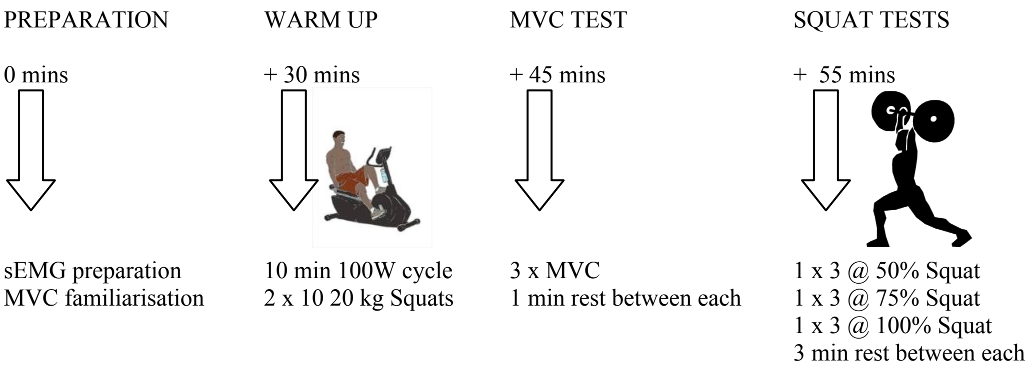

Figure 2.3. Timed summary of the reliability trial procedures.

2.2.1 Subjects

Nine male subjects were proactively recruited for this study; seven accredited strength and conditioning professionals and two University athletes; mean ± SD age of 29 ± 5 years and weight 85.7 ± 15.1 kg. All nine were skilled barbell weightlifters and had consistently performed barbell squat training to the required range of motion for at least two years. Each subject completed a health-screen questionnaire to ascertain contraindications and provided written informed consent. The University of Stirling Sports Studies Ethics Committee, in accordance with the Helsinki Declaration, approved all procedures.

2.2.2 Experimental Design

To establish the reliability of the variables under investigation, subjects performed three trials, on separate days. Each trial comprised one set of three repetitions of squat, at three different load levels, see figure 2.3. The load levels corresponded to 50, 75 and 100% of 3 repetition maximum (RM) load. Three minutes rest was taken after each set. The three trial days were performed within a seven day period, with at least one rest day prior to each trial. Subjects' 3RM load was ascertained on a separate visit prior to the reliability trials (section 2.2.3). Subjects completed the following warm up protocol before the squat trials: 10 minutes cycling on a stationary cycle ergometer (Monarch Model 818E, Varberg, Sweden) at 100 W, followed by two sets of 10 squats with 20 kg barbell. The warm up

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was then followed with a knee extension maximal isometric voluntary contraction (MVC) force assessment (section 2.2.4). The sEMG RMS amplitude was processed during this MVC. The RMS amplitude corresponding to the peak force value was later used as the reference contraction for normalisation of RMS amplitude obtained during the squat repetitions. The subjects then performed sets of squat at the three load levels. The squat was performed using an Olympic barbell, loaded with plates (Eleiko, Sweden). Subjects were instructed to perform the squat exercise using the ‘full squat’ technique (Matuszak, Fry, Weiss, Ireland, & McKnight, 2003; H. Newton, 2006). The full squat movement was defined as the hips descending below the level of the knee during the lowering phase of the movement (H. Newton, 2006). Subjects were also instructed to perform all repetitions with a self-selected tempo for each loading level. All of the squat trials were fully supervised.

2.2.3 Load

To determine the loading levels, subjects performed a 3RM squat test session between two and seven days prior to trial day one. Subjects performed a series of incrementally loaded sets, with two to three minutes between each, similar to established recommendations (Baechle, 1994). The 3RM load was taken from the final set in the series and was the maximal load that could be lifted for three repetitions with good technique. This 3RM load was converted into a system mass value, where system mass = bar mass + (0.88 x body mass), to ensure accurate relative load changes and inter-subject comparisons, as both bar and body mass are vertically displaced (Dugan *et al.*, 2004). It was assumed that 88% of body mass is involved, as the remaining 12% comprising of the shank and foot segments do not move vertically during the squat (Zatsiorsky, Seluyanov, & Chugunova, 1990). Subjects’ mean 3RM system mass load was 194.6 ± 39.6 kg.

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2.2.4 Maximal Voluntary Contraction

The MVC isometric knee extension force assessment was performed upon a dynamometer machine (Kin Com, Chattanooga, US), connected to a Biopac MP-150 data acquisition unit (Biopac Systems Inc, California, USA) similar to previous methods (J. L. Andersen & Aagaard, 2000; Hortobagyi *et al*., 1996). Subjects were strapped with a waist and shoulder harness into a seat, which was reclined at 15°. The hip angle was 90° and the knee flexion angle was 70°, with 0° corresponding to a fully extended knee. Previous research has established that MVC assessment performed with a knee angle of 70° results in both peak force and voluntary activation values (Becker & Awiszus, 2001; Pincivero, Salfetnikov, Campy, & Coelho, 2004). The seat position was adjusted for each subject so that lateral epicondyle of the knee joint was visually aligned to the rotational axis of the dynamometer. The length of the dynamometer's lever arm was individually adjusted so that the ankle attachment was firmly secured to the subjects' shank, just above the medial malleolus.

Subjects were initially familiarised with the assessment and a series of warm up contractions were performed, with increasing intensity. Subjects were instructed to slowly build up maximal force and verbally encouraged to exert maximal effort. The trial MVC's were maintained for 7 s, to allow for the slow progression of force, with 60 s rest between maximal contractions. A visual target on the dynamometer display screen was provided and immediate feedback of performance given to enhance voluntary effort and reliability as recommended by (Gandevia, 2001). Each subject performed three maximal effort MVC trials. The trial resulting in the best peak force value was taken to represent MVC force. Peak force was processed as the mean value from a 200 ms interval centred upon the peak force value. The same 200 ms interval was used to process RMS amplitude from the sEMG recording (see section 2.2.6 for details of RMS processing). This RMS amplitude value was used as the reference value for the normalisation of sEMG amplitude.

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2.2.5 Range of motion

Subjects had a flexible twin axis electrogoniometer (TSD130B, Biopac Systems Inc, California, USA) attached longitudinally to the to the left knee joint. Permanent marker pen lines were drawn between the bony landmarks of the head of fibula and the ankle lateral malleolus, and the greater trocanter and lateral epicondyle of the femur. These superficial lines represent the shank and thigh axes respectively (Zatsiorsky, 1997). The electrogoniometer endblocks were aligned to these axes and secured using adhesive tape. The electrogoniometer was connected to the MP-150 unit, via DA100C amplifier sampling at 2000 Hz with 10Hz low pass filter, a gain of 1000 and excitation ± 5V settings (Biopac systems Inc, USA). The voltage output of the electrogoniometer was calibrated from the 0° and 90° knee angles using methods similar to Piriyaprasarth *et al.* (2008). Subjects placed their left foot onto a chair and allowed their knee to naturally straighten. Extension of 0° was confirmed with a manual goniometer placed over the lateral side of the knee. Keeping the foot on the chair, and keeping the thigh aligned in the frontal plane, subjects then flexed their knee to 90°. This was again confirmed by the manual goniometer. The calibration allowed the external knee angle in the sagital plane (in degrees) to be recorded directly from the voltage output: where 0° represented an extended knee (i.e. standing upright) and an increasing value represented the external flexion angle (i.e. squatting down). Further validation of the calibration method was performed, with subjects squatting down whilst the experimenter compared the angles recorded against the manual goniometer reading. The electrogoniometer was re-calibrated if this check proved unsatisfactory through a full range of squat motion. The knee angle signal recorded during the squat trials did not require further filtering or processing. The maximum knee flexion angle corresponding to the bottom of the squat movement was taken directly for each squat repetition. The value processed was the mean of three repetitions in each set at each load level. This gave nine knee angle values per subject (three trials x three loads).

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In addition, bar displacement values were taken corresponding to 20°, 40°, 60°, 80°, 100° and 120° knee angles during each repetition of the squat at 100% 3RM load. These values were ascertained using the software data screen functions (AcqKnowledge ® 3.8.1, Biopac Systems Inc., Santa Barbara, CA). The value processed was the mean of the three repetitions. These values were used to examine the relationship between displacement and knee angle.

2.2.6 Power

A cable-extension linear position transducer device (Celesco PT5A, USA) was used to assess barbell displacement. The free end of the cable was securely attached to the left hand side of the barbell and the device itself was placed upon the floor, visually aligned to the subjects left ankle and hip. This set up ensured that the cable ran as vertically as possible during the squat movement, with the barbell placed upon the top of the shoulders. During the squat, the bar and lifter move as one system with limited acceleration and almost exclusively vertical movement, which is performed 'in-place'. Therefore, the method aimed to minimise potential methodological limitations from using a single position transducer (Cormie, McBride, *et al.*, 2007).

The transducer voltage output was connected to the MP150, sampling at 2000 Hz. The voltage was calibrated against a metre rule and converted into displacement data. The displacement data was recorded during the performance of the squat trials. Mean power was processed from displacement data during the concentric phase of the squat following previous methods (Cormie, Deane, *et al.*, 2007; Dugan *et al.*, 2004). For the specific apparatus used in this system it was established that a 3 Hz digital low pass filter was a suitable smoothing technique of the displacement data following residual analysis of the filtered signal at various frequencies (Winter, Sidwall, & Hobson, 1974; Wood, 1982), see figure 2.4.

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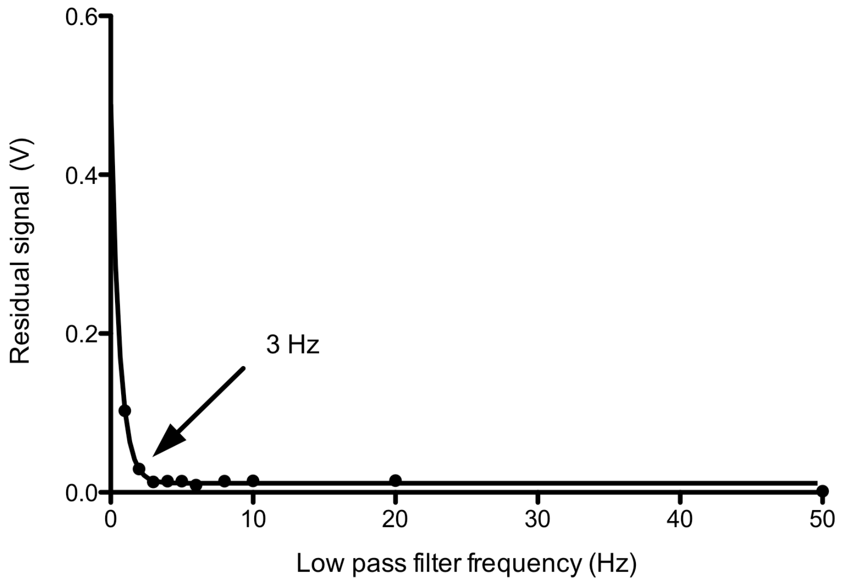

Figure 2.4. Residual analysis across low pass filter cut off frequencies from the transducer. The arrow marks 3 Hz as the optimum frequency setting for digital filtering as the long flat section to the right hand side of the arrow represents frequencies comprising only random noise sources.

Filtered displacement data was processed into power using the recording system's software functions (AcqKnowledge ® 3.8.1, Biopac Systems Inc., Santa Barbara, CA). Firstly, displacement data was derived into velocity and then acceleration using the time data from the sample rate. (Velocity = Δdisplacement/Δtime, then, Acceleration = Δvelocity/Δtime.) Acceleration was then converted into vertical force as the product of system mass and the acceleration of the system plus the acceleration due to gravity and finally, power was determined as the product of force and velocity at each time point. (Force = System mass x (Acceleration + 9.812), then, Power = Force x Velocity.) The displacement data was processed into power based upon two assumptions; 1) the bar and subject move together and 2) only in the vertical direction.

Power was processed as the mean power value from the concentric, or lifting phase of the squat. Two time points, taken from the software's screen functions, defined this phase. The start of the concentric phase was where the maximum knee angle (point of maximal

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flexion) corresponded to the point where displacement started to increase positively. The end of the concentric phase was when the knee returned to 0°, or fully extended. Figure 2.5 illustrates an example AcqKnowledge screen of displacement, power and knee electrogoniometry data from a complete squat movement cycle.

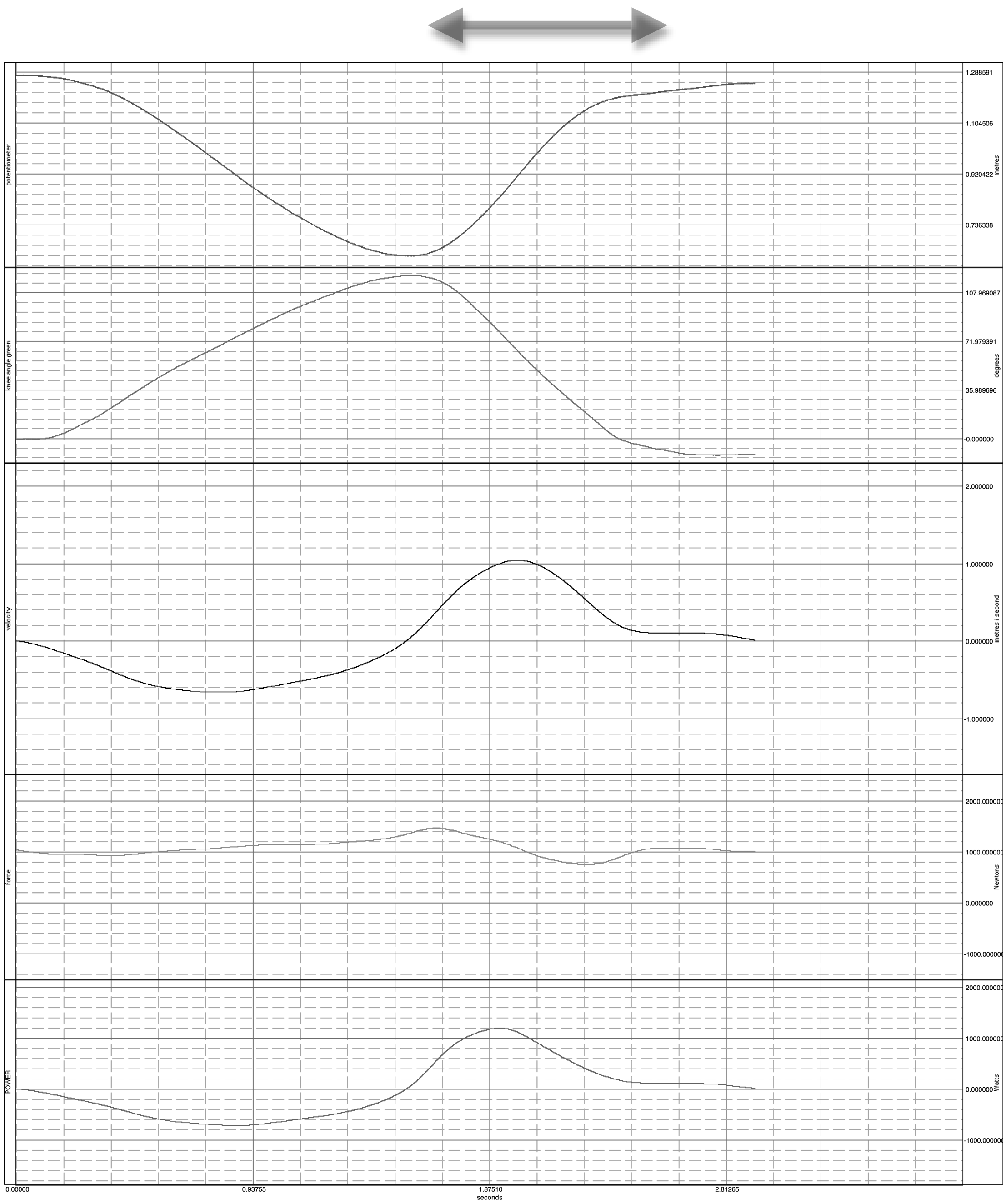

Figure 2.5. Sample data screen of displacement, knee angle and derived velocity, force and power during a single squat repetition.

Arrow above the graph marks the period of the concentric phase (0.82 s), where displacement increases concurrently with decreasing knee angle. Graph plots from top to bottom are; bar displacement (m), knee angle (°), derived velocity (m.s^{-1}), derived force (N) and derived power (W). Major grid lines on the x-axis = 0.937 s.

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Power was taken as the mean of three repetitions in each set at 75% and 100% loads. The 50% load was excluded from the analysis. This was because at this very light load, the subjects lifted the bar very easily. Consequently, the power values derived were not representative of realistic loaded squat exercise. This gave six power values per subject (three trials x two loads).

2.2.7 Surface Electromyography

Surface Electromyography (sEMG) amplitude was recorded from the *vastus lateralis* muscles. The recording was made with four Ag-AgCl 12.5 mm diameter shielded electrodes (EL258S, Biopac, USA) inserted into a bespoke engineered hard perspex mould with an inter-electrode distance of 12.5 mm (A. M. Hunter *et al.*, 2009). This array was used as conduction velocity measurements were also being taken for a separate study detailed in chapter three. The sEMG amplitude was processed from electrodes one and two in a bipolar configuration. The *vastus lateralis* is a long muscle suitable for the placement of surface electrodes. It has been shown to represent the whole quadriceps muscle group, with reliable sEMG amplitude to force relationships in both open chain (e.g. knee extension) and closed chain tests (e.g. squat) (Alkner *et al.*, 2000). The area of skin covering the approximate recording site was then shaved, abraded and cleaned. The four-electrode array was placed at two thirds down the line visualised from the greater trocanter to the lateral side of the patella, following SENIAM guidelines (Hermens *et al.*, 1999). This placement ensured that the electrodes were away from the motor point and distal (tendon) end of the muscle. The array was also positioned parallel to the approximate alignment of the *vastus lateralis* muscle fibres. The array position was marked with a permanent marker pen and attached to the cleaned skin. Each electrode was filled with conductive gel (20-30 µl) and the array was firmly secured with tape. A reference (ground) electrode was placed upon the bony patella.

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The electrode array was linked to the Biopac MP-150 acquisition unit via bespoke sEMG amplifiers. The sEMG data was sampled at 2000 Hz, automatically anti-aliased and filtered using 1Hz high pass and 500 Hz low pass analogue filters, incorporated into the hardware. The root mean square (RMS) amplitude was processed from the raw sEMG amplitude signal using a 100 ms time window, with overlapping samples. RMS amplitude was obtained using the analysis system's software (AcqKnowledge ® 3.8.1, Biopac Systems Inc., Santa Barbara, CA), as follows:

$$F(x_j) = \sqrt{\frac{\sum_{i=j-s+1}^{j} (f(x_i))^2}{s-1}}$$

Where *i* is the index for source values, *j* is the index for destination values, *n* is the number of samples, x_i, x_j are values of points on the horizontal axis, $f(x_i)$ are the values of points of a curve, F (x_j) are the integrated values of points of a curve and *s* is the number of samples to average across. Mean RMS amplitude values were taken from the whole concentric phase of the squat defined by the minimum and maximum knee angles (RMS concentric) and from a 200 ms interval centered on the 70° knee angle (RMS 70°). The mean of the three repetitions in each set was used as the final RMS amplitude value for both variables. Both RMS variables were normalised to the reference RMS value captured during pre trial MVC assessment.

2.2.8 Statistical Analyses

Descriptive statistics (mean ± SD), for maximum knee angle, power and normalised RMS amplitude were calculated for overall values (all trials and loads) and for each trial day and load separately. One-way ANOVA statistics were performed to assess differences between the three trial days for each variable. To establish the inter-trial reliability of each variable, the typical error, intraclass correlation coefficient (ICC) and coefficient of variation (CV)

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statistics were produced for knee angle, power, RMS concentric and RMS 70° using methods from Hopkins (2000b). Typical error is defined as the within-subject standard deviation between trials. To analyse the relationship between bar displacement and knee angle during the squat, displacement data from the whole range of knee angles occurring during the squat movement were collated from two trial days. One-way ANOVA of the change in displacement across knee angles was performed and differences between the trials compared. Then a linear regression was performed between displacement and knee angle for the two trial days combined. This analysis used the data from the 100% 3RM load condition as this best represented elite squat exercise performance. Statistical significance was accepted at $p<0.05$. Levels of acceptable reliability (Hopkins, 2000a) were taken as ICC of $r > 0.80$ and CV < 10%, based upon previously discussed standards (Rainoldi *et al.*, 2001; Westgard, Barry, & Quam, 1998). Statistics were performed using Minitab 15 software (USA), which reports statistics to the nearest three decimal places.

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2.4 Results

2.4.1 Reliability of Knee Angle measurements using Electrogoniometry.

The maximum knee angle across all three trial days and three loads combined was 123.7 ± 10.1°. Table 2.1 shows the maximum knee angles at each load level for all three trial days. The inter-trial typical error, CV and ICC at each load level is also given in table 2.1. There were no significant differences between trial days and load levels in maximum knee angle. The overall CV and overall ICC for all load levels combined 5.5% and r = 0.67 respectively. The low ICC compared to CV value, suggests a homogenous group. This may make ICC results sensitive to small changes in subjects' maximum knee angle. This may either increase or decrease between trial days influencing the ICC statistic, whilst the magnitude of these inter-trial changes was consistently small and so CV values were low.

Table 2.1. Mean power during squat across trial days and inter-trial typical error, CV and ICC for 75% and 100% 3RM load.

	Day 1	Day 2	Day 3	Typical error (°)	CV (%)	ICC
100%	122.1 ± 13.2	123.1 ± 11.2	122.1 ± 8.5	8.0	6.7	r = 0.60
75%	125.7 ± 11.7	127.4 ± 8.5	124.4 ± 8.5	6.4	5.0	r = 0.59
50%	120.4 ± 11.9	123.5 ± 8.9	124.9 ± 9.3	5.2	5.1	r = 0.75

Mean ± SD values during each trial and inter-trial reliability statistics for mean power during concentric phase of the squat at 75 and 100% 3RM load levels, n = 9.

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2.4.2 Relationship between Knee angle and Barbell displacement.

As expected, the bar displacement was significantly different across the range of knee angles ($F = 40.9$, $p<0.001$). There were no differences between corresponding angles from day one to two, see table 2.2. Furthermore, there was a significant relationship between knee angle and bar displacement during the barbell squat at 100% 3RM load from days one and two combined ($r^2 = 0.817$, $p<0.001$), figure 2.6. Where, bar displacement (m) = 1.39 – 0.0057 x Knee Angle (°).

Table 2.2. Bar displacement values at six knee angles across the squat range of movement.

Knee Angle	120°	100°	80°	60°	40°	20°
Day 1	0.71 ± 0.06	0.78 ± 0.07	0.90 ± 0.08	1.04 ± 0.10	1.17 ± 0.09	1.24 ± 0.08*
Day 2	0.76 ± 0.09	0.82 ± 0.08	0.94 ± 0.10	1.09 ± 0.10	1.21 ± 0.10	1.28 ± 0.10*

Values given are mean ± SD from both trial days, n = 9. * Significant change in displacement p<0.001.

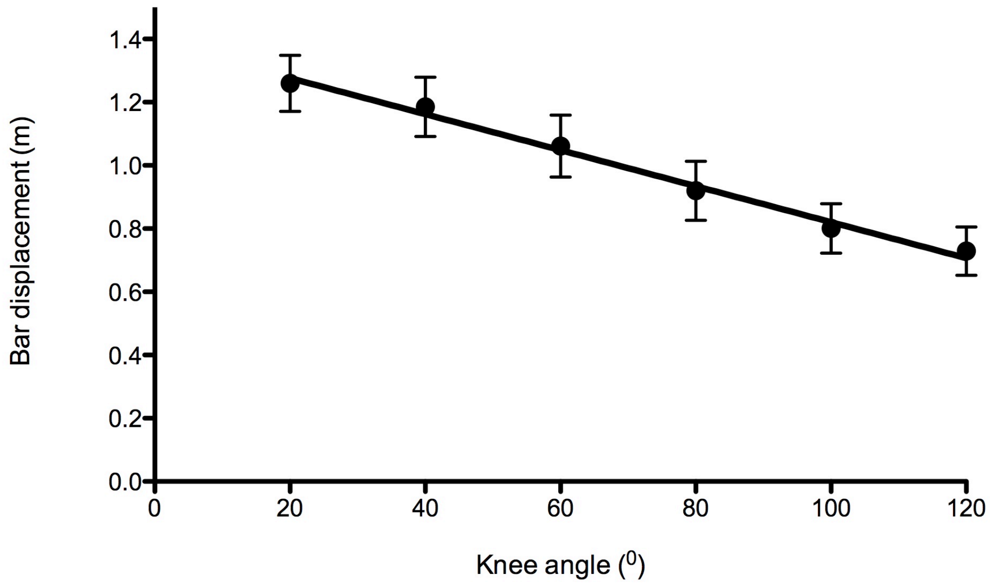

Figure 2.6. Bar displacement versus knee angle across the squat range of movement.
Combined mean ± SD values plotted from two trial days. Significant relationship, where displacement = 1.39 - 0.0057 x knee angle, ($r^2 = 0.817$, $p<0.001$), n = 9.

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2.4.3 Reliability of Power Calculations from Position Transducer Data.

Table 2.3 shows the mean power at 75% and 100% 3RM load levels for each trial day and the inter-trial typical error, CV and ICC are also given at each load level. One–way ANOVA revealed no significant differences between trial days at either load level. Power was significantly greater at 75% compared to 100% 3RM load for all three trial days combined. The overall CV and ICC for both load levels combined was 8.4% and r = 0.90 respectively. Power data from the 50% load condition was not included in this analysis as this load was very light. As a result the subjects performed the movement with submaximal effort and fast speeds and it did not represent realistic squat training exercise.

Table 2.3. Mean power during squat across trial days and inter-trial typical error, CV and ICC for 75% and 100% 3RM load.

	Day 1	Day 2	Day 3	Typical error (W)	CV (%)	ICC
100%	844.4 ± 188.7	860.8 ± 184.0	829.8 ± 170.1	73.4	7.6	r = 0.89
75%	908.7 ± 291.4	968.4 ± 218.8	978.3 ± 219.9	52.9	8.7	r = 0.92

Mean ± SD values during each trial and inter-trial reliability statistics for mean power during concentric phase of the squat at 75% and 100% 3RM load levels, n = 9.

2.4.4 Reliability of normalised RMS amplitude during squat.

RMS amplitude data was normalised relative to the peak RMS amplitude corresponding to the peak force obtained during the MVC force assessment. The MVC force values were 1026.6 ± 126.2, 1054 ± 135.2 & 1052.6 ± 110.6 N for trial days one, two and three respectively. There were no significant differences between trial days. The inter-trial CV was 3.4% and ICC was r = 0.94 for MVC. Table 2.4 shows the normalised RMS amplitude at 75% and 100% 3RM load levels for the RMS 70° and RMS concentric variables. Table 2.4 also shows the inter-trial typical error, CV and ICC at each load level

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for both variables. One-way ANOVA revealed no significant differences between trial days for normalised RMS 70° and RMS concentric at both the 75% and 100% load levels. RMS concentric and RMS 70° were significantly greater ($F = 4.50$, $p<0.001$) at 100% compared to 75% load, across all three trial days. There were no differences between RMS concentric and RMS 70° at either load level. The overall CV and ICC for both load levels combined for RMS concentric was 7.2% and $r = 0.94$ respectively. In comparison the overall CV and ICC for both load levels combined for RMS 70° was 16.4% and $r = 0.76$ respectively.

Table 2.4. Normalised RMS amplitude (RMS concentric and RMS 70° during squat across trial days and inter-trial typical error, CV and ICC for 75% and 100% 3RM load.

		Day 1	Day 2	Day 3	Typical error (%)	CV (%)	ICC
RMS concentric	100%	92.4 ± 21.5	92.0 ± 20.7	96.7 ± 24.2	5.5	6.5	r = 0.95
	75%	69.5 ± 19.9	67.4 ± 14.4	73.9 ± 18.8	5.6	7.2	r = 0.87
RMS 70°	100%	93.4 ± 28.6	87.2 ± 17.3	94.5 ± 24.6	12.8	15.5	r = 0.66
	75%	62.6 ± 18.5	63.9 ± 15.9	67.3 ± 16.9	11.3	17.9	r = 0.65

Mean ± SD values during each trial and inter-trial reliability statistics for RMS concentric and RMS 70° at 75 and 100% 3RM load levels, n = 9.

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2.5 Discussion

The first important finding was the acceptable level of inter-trial reliability found for the maximum knee flexion angles during the squat. The overall CV for all load levels was 5.5%. This is a similar to the CV of c. 5% shown by Piriyaprasarth *et al*. (2008) when assessing inter-tester reliability of static electrogoniometry knee angle measurements. However, the ICC values found in the present study were below acceptable. As a comparison, a study of inter-tester reliability from manual goniometry of static knee angles in a clinical setting showed ICC of r = 0.90 (Watkins, Riddle, Lamb, & Personius, 1991). To the researcher's knowledge, this is the first study to establish the inter-trial reliability of a flexible electrogoniometer device during dynamic resistance exercise. The disparity between the present finding and previous research may be explained by the difference in goniometer device, the dynamic versus static measurement and the inter-tester versus inter-trial investigation. The present study found maximum knee angles of 123.7±10.1° during the squat. This was taken as the deepest point of knee flexion at the bottom of the movement. This value was slightly greater than previously reported values from barbell squat video analysis of 113.9 ± 10.0° and 98 ± 13.0° (Fry, Smith, & Schilling, 2003; Zink, Whiting, Vincent, & McLaine, 2001). The difference was probably due to the exercise being defined as a 'parallel' squat in the previous research. During the parallel squat, the descent phase is limited to the point where the hip becomes level with the knee, and therefore involves less knee flexion than the full squat technique used here. Participants were also recreational weightlifters in these studies, which may influence the ability to perform the full squat depth. Other research has reported estimated values of maximum knee angles of 130° (Gullett, Tillman, Gutierrez, & Chow, 2008) and 135° (Caterisano *et al.*, 2002) for the full squat in well-trained weightlifters.

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This comparison to previous knee angle measurements during squat, that utilised 2D and 3D kinematic systems, suggests that the flexible electrogoniometer used here produced comparably accurate measurements. This is supported by a recent study demonstrating knee angle measurements during dynamic movements were highly correlated ($r = 0.95$) with measurements obtained from 2D video analysis (Bronner, Agraharasamakulam, & Ojofeitimi, 2010). The finding for the ICC statistic questions the reliability of the knee angle measurement during dynamic squat. However, the CV value of 5% represents a good level of reliability (Westgard *et al*., 1998). Combined with the evidence that the measurements accurately assessed knee angles during the dynamic movement, this supports the reliability of knee angle obtained from electrogoniometry during barbell squats.

This reliability of the knee angle measurements provides kinematic data that may be used to precisely define exercise movement for sEMG amplitude measurements during barbell squat exercise. This ensures sEMG amplitude values can be meaningfully interpreted. However, in order for the kinematics of the squat to be represented by the knee angle alone, it must be assumed that the range and timing of knee motion is co-ordinated with the overall squat movement. In other words, if the knee moves then so does the bar. In order to assess this, the relationship between the vertical displacement of the bar and the change in knee angle across the range of motion of the squat was assessed. The results showed a linear relationship between the two variables. This suggests that the movement of the knee joint represents the overall multi-joint squat movement. The subjects were all skilled weightlifters and demonstrated good squat technique. This involves the barbell remaining secure upon the shoulders of the lifter and the hip and knee joints moving synchronously throughout the whole range of motion. Recent video kinematic analysis has confirmed that the squat exercise involves simultaneous movement of the hip and knee joints (Hales,

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Johnson, & Johnson, 2009; McKean, Dunn, & Burkett, 2010). This explains how a linear relationship between the barbell displacement and knee angle is possible. Importantly, it supports the use of the knee angle variable as a kinematic representation of the whole squat movement. This enables sEMG analysis to be made with respect to defined ranges of motion of the squat, using knee electrogoniometry. This is certainly true if the results are restricted to simple descriptions of the phases of the exercise, e.g. concentric versus eccentric. The practical benefit is that electrogoniometry data is an alternative to digitised video kinematic analysis, with relatively simple set up and fast data processing compared to video methods.

The study also assessed the reliability of the mean power variable. Mean power during the concentric phase has been described as a useful representation strength training exercise performance (Bosco *et al.* 2000), and is the variable used in the investigations in this thesis. This study established acceptable reliability, as defined above, for the mean power of the squat (CV = 8.4% & ICC of r = 0.90). This compared favourably to a previous study that also used a single linear position transducer to obtain mean power values from barbell displacement (CV = 11.1% & ICC of r = 0.70) (Hori *et al.*, 2007). However, the previous study assessed mean power reliability during squat jumps, which may explain the difference in the findings. Other research has reported reliability statistics for mean power during squat jumps of ICC of r = 0.96 and CV = 4.5% (Alemany *et al.*, 2005; Sheppard *et al.*, 2008). These reliability levels were similar to the present findings. However, mean power was derived from force plate and two linear position transducers in these studies.

The mean power values during the squat estimated in this study are comparable to reported values from research using similar loads (Zink, Perry, Robertson, Roach, & Signorile, 2006). Harris, Cronin, & Hopkins (2007) reported mean power at 100% load of c.1000W

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processed using the same methods as the present study. However, the squat was performed 'explosively', which would explain the slightly higher power values compared to the present study (850W at 100% 3RM). Methodological issues exist in estimating power from displacement data alone, as force values must be obtained from acceleration derived from displacement, and not directly from force plate or transducer measurements (Cormie, Deane, *et al.*, 2007). In addition, the use of a single linear position transducer limits the analysis to vertical displacement. Therefore, it was not possible to determine how much horizontal motion occurs during the squat, nor how much horizontal movement contributes to mean power. Horizontal movement must be assumed to be minimal for the mechanical processing to be valid from a single linear position transducer (Cormie, Deane, *et al.*, 2007). However, in support of the current methods, previous studies showed no significant differences between mean power values during heavy squats obtained from a system using two linear position transducers (measuring both horizontal and vertical) versus one vertical only transducer (Cormie, McBride, *et al.*, 2007). This suggests minimal horizontal displacement and/or velocity of the barbell occurs during squat. This is likely to be because of relative low levels of vertical acceleration during heavy squats, compared to other weightlifting or jump exercises, allowing for more control of the movement. No 3-D video kinematic research was found reporting horizontal versus vertical motion of the bar during squat. All together, despite acknowledged limitations, the processing of mean power during squats using bar displacement data from a single linear position transducer is supported by evidence. In addition, the levels of reliability were shown to be above acceptable standards.

The variability presented in this study represents both physiological and motor skill variability, in terms of the lifters' performance, as well as the methodological variability of the instruments and processing. This is because the speed of the squat movement was not

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controlled. The range of squat motion was instructed as full squat, but not precisely controlled between subjects or trials. Therefore, an assumption was made that the skilled subjects would be consistent in their movement. This could be construed as a methodological weakness. However, given the aim of this study was to establish the reliability of an analysis system to monitor barbell resistance exercise, the lack of controlled speed and range means that values reflect much the variability likely to occur during training sessions. As discussed in chapter one, real time monitoring has potential importance for the investigations of the acute NM response to strength training. This is because power represents resistance exercise performance (Bosco *et al.*, 2000) and sEMG amplitude can track muscle activity changes as they occur during sessions, from the onset of exercise. The advantage of using the current system is that NM investigations of dynamic resistance exercise are not reliant upon non-specific tests, such as isometric MVC's post session. Instead, acute NM responses may be analysed directly from the exercise performance within the training session (Cairns *et al.*, 2005).

The inter-trial reliability of sEMG amplitude recordings were also assessed, using *vastus lateralis* normalised RMS amplitude measurement. Previous research has reported the inter-trial ICC of r = 0.82 for the *vastus lateralis* RMS amplitude during dynamic contractions (Larsson *et al.*, 2003; Rainoldi *et al.*, 2001). Additionally, *vastus lateralis* RMS amplitude was also shown to have higher ICC values in comparison RMS amplitude from the *rectus femoris* and *vastus medialis* (Larsson *et al.*, 1999). However to our knowledge, no study has reported reliability for normalised RMS amplitude of the *vastus lateralis* muscle during loaded squat exercise. This study showed reliability represented by the ICC and CV statistics was above the acceptable cut off for the RMS concentric variable (CV = 7.2% and ICC of r = 0.94). In comparison the RMS 70° variable was below acceptable (CV = 16.4% and ICC of r = 0.76). This is probably explained by the averaging

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of the RMS value from a larger epoch for RMS concentric versus RMS 70° resulted in reduced measurement variation. ICC values found in this study were higher than previously reported for other dynamic resistance exercises (r = 0.67) (Worrell *et al.*, 1998) and similar to reported isomeric values (r > 0.80) (Rainoldi *et al.*, 2001).

The greater RMS amplitude value found during 100% compared to 75% load was expected. In addition, normalised RMS amplitude of c. 80% (in reference to peak RMS during MVC force test) was similar to previous reported findings of *vastus lateralis* normalised RMS amplitude of 85% during barbell squats with similar loads (Gullett *et al.*, 2008). Dynamic sEMG analysis has established methodological issues (Farina, Merletti, *et al.*, 2004). For example, the electrode placement may vary between subjects and trials and the muscle length and shape may change during dynamic contractions. However, following the recommended set-up and preparation, the use of normalisation procedures minimises these issues (De Luca, 1997). The current data supports the reliability of sEMG amplitude during dynamic squat exercise using skilled lifters. Specifically, the normalised RMS amplitude from the *vastus lateralis* muscle is shown to be reliable. However, the current data supports processing RMS amplitude over the entire concentric phase to ensure acceptable reliability.

2.6 Summary and Conclusion

In summary, this study has established acceptable levels of reliability during barbell squat exercise of knee angle measurements using electrogoniometry, mean power processed from bar displacement data and RMS amplitude of the *vastus lateralis* processed from the concentric phase of the movement. In addition, the relationship between knee angle and bar displacement suggests the knee joint electrogoniometry is a suitable descriptor of multi-joint squat kinematics. The reliability of the system allows for meaningful

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monitoring of sEMG amplitude and mean power during barbell squat exercise, where any changes within and between sessions may be assessed with confidence. Furthermore, the reliability of the measurements has been tested using the specific elite training methods this thesis aims to investigate. Therefore, the combined biomechanical and sEMG analysis system may be effectively used to investigate acute NM responses to resistance exercise sessions (Cairns *et al.*, 2005). This data may compliment information gleaned from a NM assessment battery utilised before and after training sessions.

Chapter Three

Reliability of Muscle Fibre Conduction Velocity during barbell squat exercise

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3. Reliability of muscle fibre conduction Velocity during dynamic barbell squat exercise.

3.1 Introduction

Investigations of neuromuscular (NM) responses during resistance exercise may further understanding of the adaptation processes that lead to improved strength and athletic performance. Specifically, the NM responses during repetitions of resistance exercise may reveal the muscle activation and possible resultant fatigue required to optimise chronic adaptation (McCauley *et al.,* 2009). Surface electromyography (sEMG) recordings processed into amplitude and frequency variables provide information of the NM response to sustained or repeated contractions (Bigland-Ritchie *et al.*, 1992; Gonzalez-Izal *et al.*, 2010; Moritani *et al*., 1986). Increased sEMG amplitude implies additional motor unit recruitment and/or firing rate, typically to maintain force generation during the sustained sub-maximal contractions (Moritani *et al.*, 1986; Sogaard *et al.*, 2006). Increased sEMG signal frequency may also indicate greater motor unit firing rates (Enoka & Stuart, 1992). Decreased amplitude suggests de-recruitment of motor units and/or reduced firing rate, normally due to fatigue in maximal contractions (Moritani *et al.*, 1986). In contrast, decreased signal frequency suggests a slowing of muscle fibre conduction velocity (MFCV), as frequency is related to MFCV due to the influence of action potential propagation speed upon the sEMG signal power spectrum (Dimitrova & Dimitrov; 2003 Farina, 2006).

Similar to frequency variables, MFCV provides information of NM responses and fatigue processes during exercise (Farina *et al.*, 2007). However, MFCV can be directly measured using bespoke sEMG electrode arrays and processing methods (Farina, Pozzo, Merlo, Bottin, & Merletti, 2004). For example, studies have demonstrated changes in MFCV

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during sustained isometric exercise (Arendt-Nielsen *et al.*, 1989) and MFCV decreased over 10% from an initial value of 4.4 $m.s^{-1}$ during four minutes of sustained sub-maximal cycling (Farina, Pozzo, *et al.,* 2004). The MFCV value represents the propagation speed of the action potential down the length of the muscle fibre, from the site of innervation. Action potential propagation is influenced by both the size of muscle fibre recruited and fatigue related processes within the muscle. Firstly, faster action potential conduction occurs down larger volume muscle fibres. Fast twitch (type II) fibres are greater in size than slow twitch (type I). As a result, MFCV is an indicator of the type of motor units recruited, as a Hanneman size principal parameter. Higher MFCV values represent a greater proportion of fast twitch motor unit activation, based upon studies showing a relationship ($r = 0.87$) between evoked twitch contraction force and MFCV (Andreassen & Arendt-Nielsen, 1987; Troni et al., 1983). MFCV also increases in proportion to dynamic contraction power (Macdonald *et al.*, 2008) or pedal force during cycling (Farina, Macaluso, *et al.*, 2004), and in proportion to force during dynamic leg press exercise (Pozzo *et al.*, 2004). Secondly, slower action potential propagation occurs as a result of physiological processes in the muscle fibre membrane (Fitts, 1994; K. Masuda *et al.*, 1999). Specifically, lowering of muscle pH results in changes to the Na^+ and K^+ ion balance in the extracellular space, which in turn slows action potential propagation (Brody *et al.*, 1991). Therefore a reduced MFCV value represents peripheral fatigue in the muscle. For example, MFCV decreased during sustained isometric contractions (K. Matsuda *et al.*, 1999), where metabolite accumulation is likely to occur.

The advantage of direct measurement of MFCV over sEMG frequency variables is that is does not require special signal filtering and Fast Fourier transform processing that rely upon signal stationarity (Dimitrova & Dimitrov, 2003; Farina, Foscu, *et al.*, 2002). Therefore, MFCV may provide a more accurate representation of action potential

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propagation, and less interpretation than sEMG frequency analysis (Merletti, Knaflitz, & De Luca, 1990). For example, Lowery *et al.* (2002) showed that MFCV reduced less than sEMG frequency during sustained isometric elbow flexion, particularly during high force contractions. During fatigue, changes in recruitment influences sEMG frequency independent of changes in MFCV, due to the position of the active motor units within the muscle. These issues are amplified further during dynamic contractions, due to changes in muscle length and joint position (Farina, 2006; Farina, Foscu, *et al.*, 2002). Therefore, MFCV measurements may be preferable to frequency analysis, particularly during dynamic contractions (Pozzo, Alkner, Norrbrand, Farina, & Tesch, 2006), and those involving high forces, such as resistance exercises.

Analysis of MFCV during resistance exercise is of interest as activation of large (type II) motor units is fundamental to adaptation (Aagaard, 2003; Sale, 1988). Peripheral fatigue detected by MFCV may also indicate stimulus for adaptation of muscle protein synthesis (McDonagh & Davies, 1984; Schoenfeld, 2010). Whole body, free-weight resistance exercises, such as barbell squat involve moving the load with multi-joint leg extension, whilst controlling posture. Evidence exists that specific differences in motor unit recruitment and fatigue occur in tasks involving control of position versus supported loads (Maluf & Enoka, 2005). Therefore, specific investigations of MFCV during barbell squat may further understanding of NM responses to whole body resistance exercises used by elite athletes and also clinical rehabilitation patients. Prior to using MFCV during investigations of resistance exercise training, the primary aim of this study is to establish the reliability of MFCV measured during barbell squat. This is because, the reliability of MFCV measures during dynamic barbell resistance exercise has not been assessed. Previous research has reported MFCV reliability from isometric knee extensions, showing within-subject coefficient of variation (CV) between 4.6 - 7.9% and between-trial

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intraclass correlation (ICC) of r = 0.82 (Rainoldi *et al.*, 2001). In addition, Macdonald *et al.* (2008) reported MFCV between-trial CV = 5.5% and ICC of r = 0.78 during submaximal cycling exercise. The present study is also used as a preliminary investigation of the possible changes in MFCV during barbell squat in response to incremental load and fatigue. This may help the following studies understand MFCV measures during barbell resistance exercise training sessions.

3.1.1 Research Questions

1) What is the reliability of the MFCV variable of the *vastus lateralis* during the barbell squat and squat jump exercises?

2) Is the positive relationship between force and MFCV of the *vastus lateralis* observed in isometric knee extensions also observed during incremental loaded barbell squat?

3) Is the expected decline in MFCV of the *vastus lateralis* during a maximal fatiguing barbell squat jump exercise observable?

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3.2 Methods

PREPARATION	WARM UP	MVC TESTS	SQUAT TESTS
0 mins	+ 30 mins	+ 45 mins	+ 55 mins
sEMG preparation MVC familiarisation	10 min 100W cycle 2 x 10 20 kg Squats	3 x MVC 1 x 50% MVC 1 x 75% MVC 1 min rest between each	1 x 3 @ 50% Squat 1 x 3 @ 75% Squat 1 x 3 @ 100% Squat 3 min rest between each 1 x max reps @ 50% Squat Jump

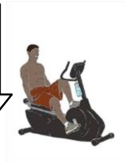

Figure 3.1. Timed summary of the procedures to established MFCV reliability during squat.

3.2.1 Subjects

The same nine male subjects described in chapter two also performed these trials. Table 3.1 shows the physical characteristics of the subjects. Each subject completed a health-screening questionnaire to ascertain contraindications and provided written informed consent. In accordance with the Helsinki Declaration, the University of Stirling Sports Studies Ethics Committee approved the procedures.

Table 3.1 Descriptive data of the subjects' physical characteristics.

Age (years)	Weight (kg)	Height (cm)	Sum of 7 skinfold sites (mm)	Knee extension MVC force (N)
29 ± 5	86.3 ± 14.9	178.6 ± 8.6	58.2 ± 16.8	1064.4 ± 114.5

Values given as mean ± SD, n = 9.

3.2.2 Experimental design

To establish the inter-trial reliability of the MFCV variable, and to investigate MFCV response during dynamic squats to increasing force and fatigue, subjects performed the following trial on two separate days: Three repetitions of isometric knee extension contractions at 100% of maximal voluntary contraction (MVC) force, followed by one repetition at 50% and 75% of MVC force each. One set of three repetitions of barbell

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squats at 50, 75 and 100% of 3RM load, and finally one set of fatiguing loaded squat jumps, see figure 3.1. One minutes rest separated the isometric knee extension repetitions and three minutes rest was taken after each set of squats. The loaded squat jumps were performed with 50% 3RM load, until failure. The trial days were performed within seven days, with at least one rest day between each trial. Subjects' 3RM load was ascertained on a separate visit prior to the reliability trials and described in full in section 2.2.3. The subjects used the same loads as the previous study (chapter two).

3.2.3 Experimental procedures

Subjects were first prepared with a flexible electrogoniometer attached to the lateral left knee as described in 2.2.5 and a sEMG electrode array was attached over the right *vastus lateralis* muscle (see 3.2.4 below). Subjects completed the following warm up protocol before the squat trials: 10 minutes cycling on a stationary cycle ergometer (Monarch Model 818E, Varberg, Sweden) at 100 W, followed by two sets x 10 squats with 20 kg barbell. The warm up was then followed with three repetitions of knee extension MVC force assessment. Full details of this procedure and processing are given in section 2.2.4. The sEMG root mean square (RMS) amplitude and MFCV measurements were taken from all MVC and submaximal isometric knee extension repetitions; see 3.2.4. Force levels were defined as 50, 75 and 100% of MVC. The MVC repetitions were performed first so that the target force levels for the 50% and 75% MVC isometric knee extensions could be calculated. During the submaximal repetitions, performed on the same equipment as the MVC's, subjects were instructed to build up to the target force level and maintain that value as constantly as possible. The contractions were maintained for seven seconds to enable RMS amplitude and MFCV measurements to be taken from a period of stable force production. Visual and verbal feedback was given to aid the subjects in achieving stable force.

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The subjects then performed the three sets of squat, followed by the fatiguing set of squat jumps. The squat was performed using Olympic barbell, loaded with plates (Eleiko, Sweden). Subjects were instructed to perform the squat and squat jump exercise using the 'full squat' technique (Matuszak *et al*., 2003; H. Newton, 2006). The full squat movement was defined as the hips descending below the level of the knee during the lowering phase of the movement (H. Newton, 2006). Subjects were also instructed to perform all squat repetitions with a self-selected tempo for each loading level. Subjects were instructed to perform the squat jumps with maximal effort from the beginning of the test. The aim was to jump as high as possible, keeping the barbell securely upon the shoulders and landing consistently in the same position for all repetitions. All repetitions were fully supervised.

A cable-extension linear position transducer device (Celesco PT5A, USA) was used to measure barbell displacement during the dynamic squat and squat jump trials. The free end of the cable was securely attached to the left hand side of the barbell and the device itself was placed upon the floor, visually aligned to the subjects left ankle and hip. This set up ensured that the cable ran as vertically as possible during the squat movement, with the barbell placed upon the top of the shoulders. Mean power from the concentric phase of each movement was determined from the displacement data, as described in full in section 2.2.6. RMS amplitude and MFCV measurements were taken during the concentric phase of squat and squat jump repetitions; see section 3.2.4. During the squats, mean power, RMS amplitude and MFCV values were taken as a mean of the three repetitions. Squat load levels were defined as 50, 75 and 100% of 3RM. During the squat jump, mean power, RMS amplitude and MFCV values were taken at the start (mean of first three repetitions), middle (mean of middle three repetitions) and end (mean of last three repetitions) of the trial for each subject. These values were used to represent three levels of fatigue, where 'start' is fresh, 'middle' is partially fatigued, and 'end' is fully fatigued.

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Following findings from Stewart, Macaluso, & De Vito (2003), the timings of the warm up, rest intervals and test running order were designed purposefully and controlled rigorously to minimise the influence of muscle temperature upon MFCV (Gray, De Vito, Nimmo, Farina, & Ferguson, 2006; Stewart *et al.*, 2003). Room temperature was also monitored to ensure consistency between trial days.

3.2.4 RMS amplitude and Muscle Fibre Conduction Velocity Procedures

The following method, previously described by (A. M. Hunter et al., 2009), was used to obtain both RMS amplitude and MFCV from the sEMG signal. Four Ag-AgCl 12.5 mm diameter shielded electrodes (EL258S, Biopac, USA) were inserted into a bespoke engineered hard perspex mould with an inter-electrode distance of 12.5 mm. From which, four single sEMG signals were recorded and converted into three pairs of bipolar signals following Lowery *et al.* (2002), see figure 3.2.

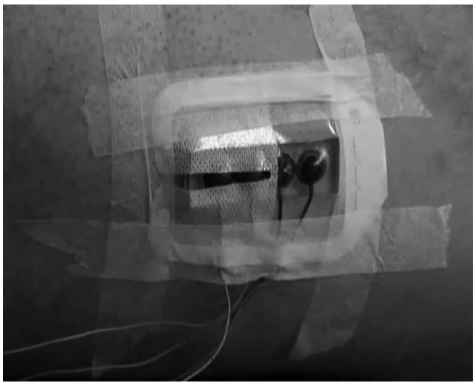

Figure 3.2. Photo showing the perspex mould electrode array placement upon vastus lateralis.

The four-electrode array was placed at two thirds down the line visualised from the greater trocanter to the lateral side of the patella, following SENIAM guidelines (Hermens *et al.*, 1999). This placement ensured that the electrodes were away from the motor point and distal (tendon) end of the muscle. Initially, dry silver inserts were placed into the electrode array, which was temporarily secured parallel to the approximate alignment of the *vastus lateralis* muscle fibres. Test recordings and MFCV values from seated voluntary contractions were obtained until the optimal array placement was determined. This

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placement was where the sEMG signals were highly correlated. The placement was marked with permanent marker pen and the array filled with conductive gel (20-30 µl) was securely placed using Tegaderm™ adhesive dressing (3M, USA) and additional tape. A reference (ground) electrode was placed upon the bony patella.

The electrode array was linked to the Biopac MP-150 acquisition unit via bespoke sEMG amplifiers. The sEMG data was automatically anti-aliased and filtered using 1 Hz high pass and 500 Hz low pass analogue filters, incorporated into the hardware. Each activity was sampled at 2000 Hz. The RMS amplitude was processed from the raw sEMG amplitude of signal one using a 100 ms averaging time window, with overlapping samples, as described in 2.2.7. RMS amplitude values during the 50, 75 and 100% MVC isometric knee extensions were taken as the mean RMS from a 200 ms time interval. This was centred upon the peak force level during the MVC, and a stable portion of the target force level during the submaximal repetitions. RMS amplitude values during the dynamic squat and fatiguing squat jump trials were taken as the mean RMS from a 200 ms time window centred upon the 70° external knee angle during the concentric phase and from the whole concentric phase. All RMS amplitude values were normalised to the reference RMS value captured during pre trial MVC's. The time interval for MFCV processing during the isometric trials corresponded to the RMS processing sample. During the squat and squat jump repetitions, MFCV was processed from a smaller 100 ms time window, centred upon the 90° external knee angle. This greater knee flexion angle in the dynamic, compared to the isometric condition was chosen to limit the speed of movement occurring during the epoch of the MFCV measurement. At a knee angle of 90° the squat and squat jump will involve less acceleration than at 70° (Zink *et al.*, 2001). This was an attempt to limit processing issues with changes in muscle architecture during MFCV processing intervals (T. Masuda *et al.*, 2001).

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MFCV values were processed following previous methods (A. M. Hunter *et al.*, 2009; Lowery *et al.*, 2002). The data from the three separate sEMG signals were first processed into two double differential signals. For accuracy, both double differential signals were up-sampled to 20 kHz to reconstruct the original un-filtered signal using Matlab software (Mathworks Inc, USA) *interpft* function. The double differential signals were then processed using the Matlab *xcorr* function. This process analysed the time delay between peaks in the two signals that were highly correlated (r>0.80). In other words, identifying points from each signal that were time-delayed versions of each other, see figure 3.3. From the time delay, MFCV was calculated as the distance between electrodes is known; where MFCV = electrode pair distance / estimated time delay.

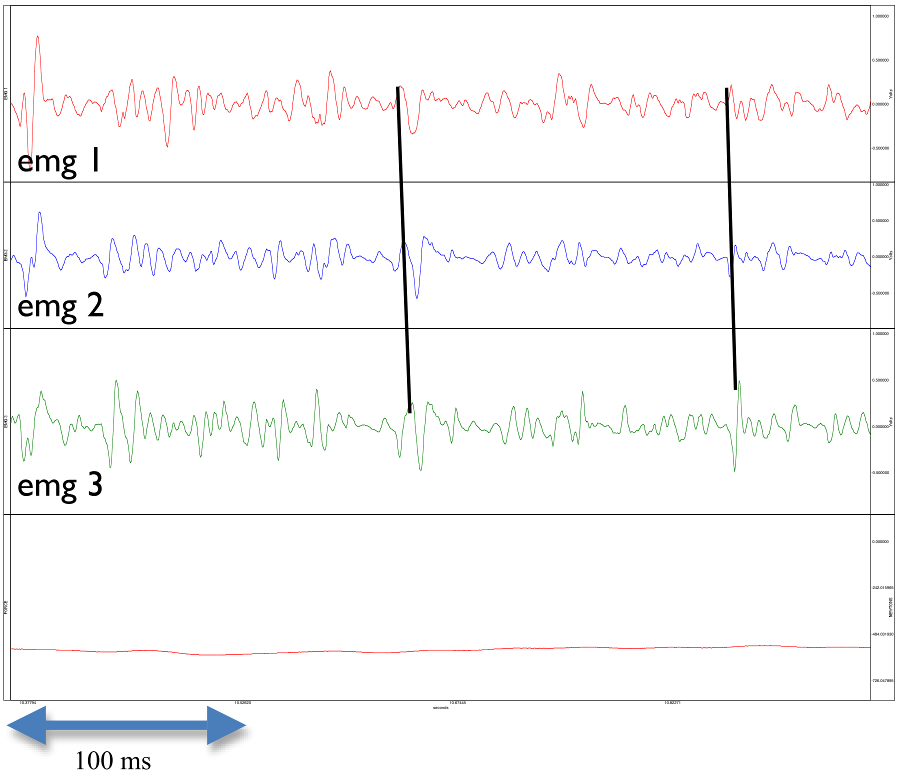

Figure 3.3. Sample sEMG data from isometric knee extensions used for MFCV processing.
Shows the raw sEMG data from three signals, as labelled. The lines marked on the figure illustrate the time delay between each signal at points where all three signals peak with the waveforms having similar shape. The bottom waveform, illustrates a flat, stable portion of the force measurement from which the MFCV measurement is processed.

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3.2.5 Statistical methods and analysis

Descriptive statistics (mean ± SD) from trial day one were calculated for MFCV and RMS amplitude during both isometric and dynamic squat and squat jump trials. MFCV data was obtained from only five subjects during isometric trials and inter-trial day analysis was possible for only seven of the subjects for squat and squat jump trials due to methodological issues. Specifically, the inability to obtain correlated signals in both the isometric and dynamic condition was not possible in some subjects. To compare differences in RMS amplitude and MFCV between force levels during isometric knee extension, load levels during squat, and fatigue levels during squat jump, a general linear model ANOVA (repeated measures) procedure was performed. *Post hoc* Tukey's tests were performed following significant statistics. Comparisons between trial days were possible for seven subjects. To establish the level of reliability in MFCV, inter-trial day typical error, intraclass coefficient (ICC) and coefficient of variation (CV) statistics were analysed for squat from the 100% 3RM load level and the start of the squat jumps (mean of first three repetitions) (Hopkins, 2000b). Typical error is defined as the within-subject standard deviation between trials. Statistical significance was accepted at $p<0.05$. Following the previous chapter, acceptable levels of reliability were taken as ICC of $r > 0.80$ and CV < 10% (Rainoldi *et al.*, 2001; Westgard *et al.*, 1998). Statistics were performed using Minitab 15 software (USA), which reports statistics to nearest three decimal places.

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3.3 Results

3.3.1 MFCV inter-trial reliability

MFCV during squat and squat jump (non-fatigued) showed acceptable inter-trial day reliability (Hopkins, 2000a) (see Table 3.2).

Table 3.2. Squat and squat jump MFCV across trial days and inter-trial day typical error, CV and ICC statistics.

	Day 1 ($m.s^{-1}$)	Day 2 ($m.s^{-1}$)	Typical error ($m.s^{-1}$)	CV (%)	ICC
Squat	5.6 ± 1.2	6.0 ± 1.3	0.49	9.6	r = 0.84
Squat Jump	5.4 ± 0.8	5.5 ± 1.0	0.58	12.1	r = 0.60

Values for mean ± SD (n = 7), typical error, CV, and ICC.

For comparison, the MFCV during the isometric knee extension MVC was 7.2 ± 1.3 $m.s^{-1}$ (n = 5), with typical error = 0.71 $m.s^{-1}$, CV = 9.8% and ICC of r = 0.72.

3.3.2 MFCV and RMS between Force, Load and Fatigue conditions

The increase in MFCV and RMS with isometric force is shown in Figure 3.4 A and B. As expected, force values between the 50, 75 and 100% MVC levels were significantly different (F = 53.2, $p<0.001$), at 525.5 ± 62.2, 788.8 ± 69.9, and 1048.0 ± 124.7 N respectively. The MFCV significantly increased with force level (F = 9.00, p = 0.009), which was 4.7 ± 1.4, 5.6 ± 1.5, and 6.2 ± 1.8 $m.s^{-1}$ at 50, 75 and 100% MVC respectively. Normalised RMS amplitude also significantly increased with force (F = 57.68, $p<0.001$). These were 45.7 ± 11.6, 71.48 ± 14.3, 100 ± 0 % at 50, 75 and 100% MVC respectively. During the dynamic squat at 50, 75 and 100% of 3RM load MFCV was 5.5 ± 1.0, 5.0 ± 1.1, and 5.3 ± 1.1 $m.s^{-1}$ respectively, which was not different between load levels. In contrast, normalised RMS amplitude significantly increased (F = 51.50, $p<0.001$) with load

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level. Normalised RMS values were 56.5 ± 13.2, 75.6 ± 9.9 and 102.2 ± 15.7 % at 50, 75 and 100% of 3RM load respectively. The change in normalised RMS amplitude compared to MFCV between squat loads is depicted in Figure 3.4 C and D. Loads lifted, as expected, were significantly different between 50, 75, and 100% 3RM load levels ($F = 26.65$, $p<0.001$) at 99.4 ± 18.9, 149.1 ± 28.1 and 199.7 ± 37.5 kg respectively. Mean power was significantly different between 50, 75 and 100% 3RM load ($F = 12.47$, $p<0.001$), which were 749.2 ± 128.6, 974.7 ± 220.2 and 799.9 ± 163.3 W respectively. *Post hoc* tests revealed that power during 75% load was significantly higher than at 50 and 100% 3RM load.

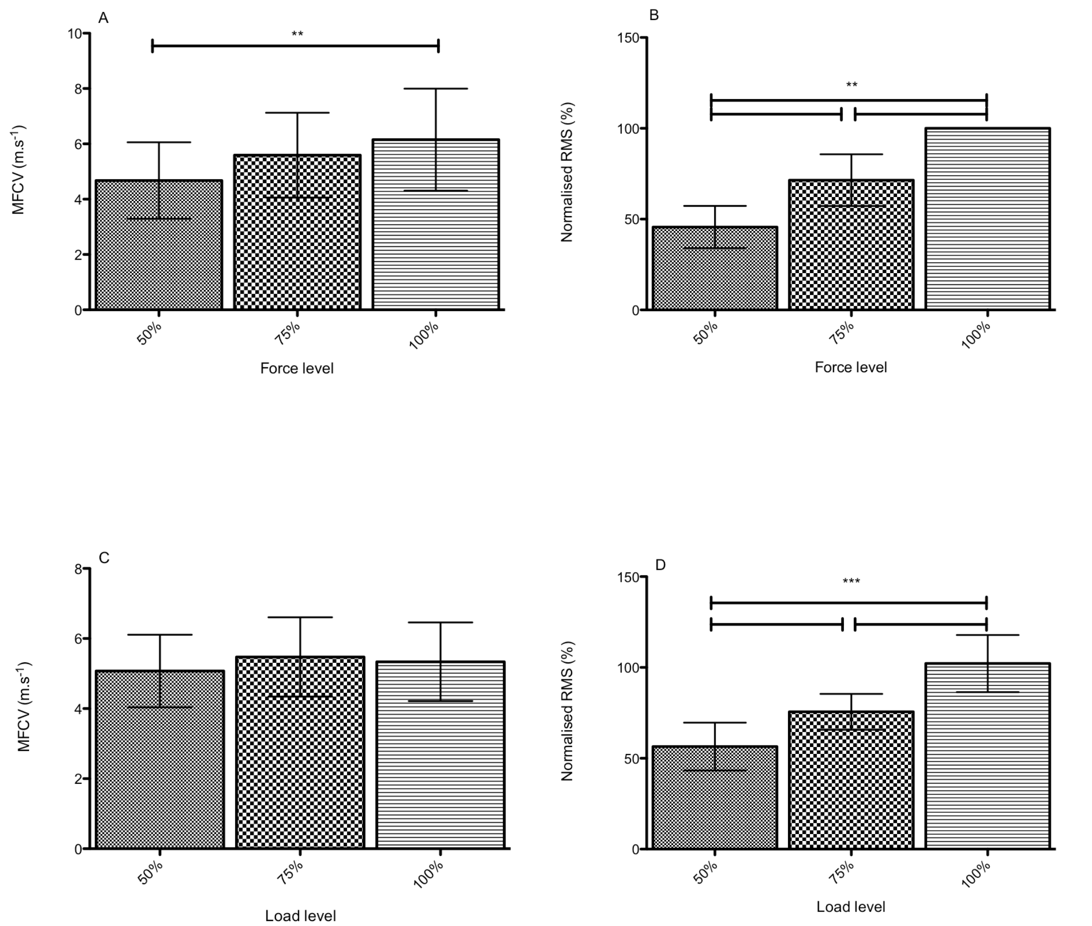

Figure 3.4. A) MFCV and B) RMS at 50, 75 and 100% of isometric knee extension MVC force. C) MFCV and D) RMS at 50, 75 and 100% of 3RM load during dynamic squat.
A&B: ** significant difference ($p<0.01$) in MFCV and ($p<0.001$) in RMS amplitude between force levels. Values given are mean ± SD for trial day one, n = 5. C&D: *** significant difference ($p<0.001$) in RMS between load levels. Values given are mean ± SD for trial day one, n = 9.

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Table 3.3 shows the descriptive data for mean power, MFCV and normalised RMS amplitude across the three levels of fatigue during the squat jump trial. The mean ± SD number of squat jumps performed was 26.2 ± 5.2 repetitions during trial day one. MFCV was significantly different between fatigue levels ($F = 11.25$, $p<0.001$) and *post hoc* analysis revealed the MFCV at the end was lower than the start and middle. Mean power ($F = 32.02$, $p<0.001$) also significantly reduced across fatigue levels, whilst no differences were found for normalised RMS amplitude. Figure 3.5 shows the change in each variable relative to the start (non-fatigued condition).

Table 3.3. Squat jump mean power, MFCV, and normalised RMS amplitude across fatigue levels.

	Fatigue level		
	Start	Middle	End
Power (W)	1920 ± 143	1709 ± 248	1407 ± 254**
MFCV (m/s)	5.7 ± 1.4	5.2 ± 1.2	4.6 ± 1.0*
RMS (%)	106.3 ± 19.6	104.4 ± 20.2	99.6 ± 16.8

Values given are mean ± SD for trial day one, n = 9. * Significant difference ($p<0.01$) between the start and end repetitions. ** Significant difference ($p<0.001$) between, start, middle and end repetitions.

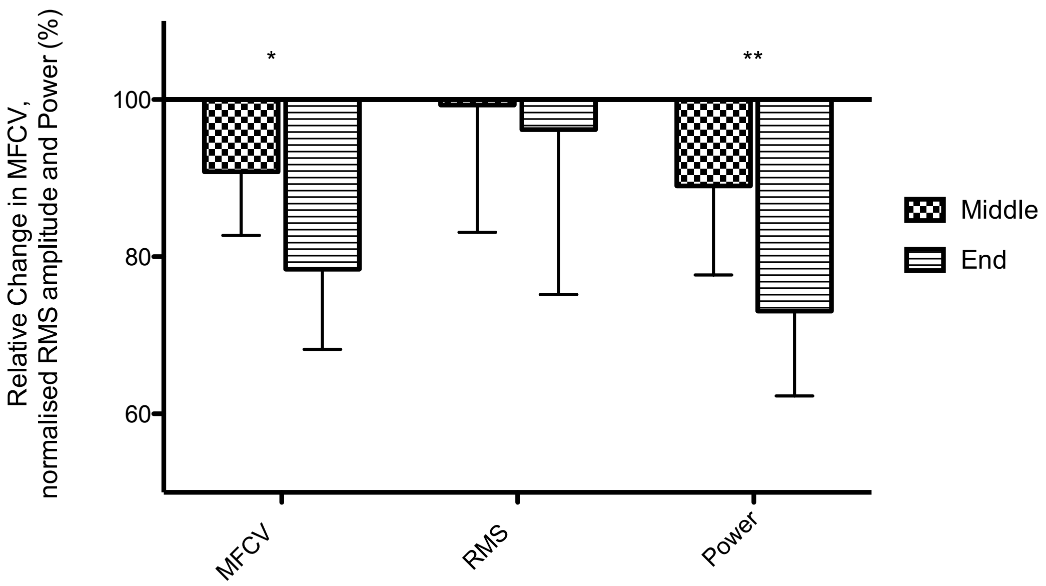

Figure 3.5. Relative changes in MFCV, RMS and Power across fatiguing squat jump trials.
Values given are mean ± SD relative to start for trial day one, n = 9. * Significant difference ($p<0.01$) between start and end repetitions and ** ($p<0.001$) between, start middle and end repetitions.

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3.4 Discussion

The MFCV values found between 5.4 and 6.0 $m.s^{-1}$ during dynamic squat and squat jump exercise were within previously shown normal physiological ranges (Arendt-Nielsen *et al.*, 1989; Troni *et al.*, 1983). The findings show reliability of MFCV measurement from *vastus lateralis* during the squat was above acceptable levels (CV = 9.6% and ICC of r = 0.84). This were similar findings to previously reported inter-trial ICC's (r = 0.82) during isometric knee extensions (Rainoldi *et al.*, 2001) and the isometric data in this study. In contrast, during dynamic squat jump MFCV reliability was below the acceptable cut-off (CV = 12.1%, ICC of r = 0.60). These findings support the reliability of directly measured MFCV during dynamic squat movements. However, during squat jump MFCV may be less reliable. The greater velocity of movement may explain the difference in MFCV reliability between the exercises. This is due to possible greater muscle length changes occurring within the interval from which MFCV is processed during squat jump, as this may alter the alignment of the fibres in relation to the surface electrode placement (Kossev *et al.*, 1992).

The MFCV during barbell squats at increasing load level did not change, whilst normalised RMS amplitude values increased with load. In contrast, both MFCV and normalised RMS amplitude increased with isometric knee extension force, following previous findings (Pozzo *et al.*, 2006). During muscle contractions, greater normalised RMS amplitude is related to additional motor unit recruitment and/or firing rates to produce greater force. In addition, increased MFCV in relation to greater isometric force suggests an increase in the proportion of type II motor units recruited (Andreassen & Arendt-Nielsen, 1987). During the dynamic squats, increased load implies increased muscle force, and so it is perhaps surprising that only normalised RMS amplitude increased with load level. The unchanged MFCV with increased squat load does not follow previous findings. For example, these

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demonstrated a relationship between force and MFCV during cycling and leg press exercise (Farina, Macaluso, *et al.*, 2004; Pozzo *et al.*, 2004). The lack of a relationship between MFCV and squat load in the present study was most likely due to methodological issues during the dynamic measurement. Specifically, relative movement of the electrode over the muscle fibres may influence the motor unit detectable under the electrode array. The electrode may also move over the innervation zone, disrupting the signal (Farina *et al.*, 2007; Farina, Pozzo, *et al.*, 2004). For this reason, T. Masuda *et al.* (2001) argued that the cross-correlation of the MFCV signal must be stable across a range of speeds at specific joint positions in order for the MFCV to reflect changes in motor unit recruitment during dynamic contractions.

Another possible explanation for unchanged MFCV is that power and not load influences the type motor unit recruitment during dynamic squats. Cycling pedal power (increases and decreases) has been related to quadriceps MFCV measures (Farina, Macaluso, *et al.*, 2004; Macdonald *et al.*, 2008). The present study found similar MFCV and power values during 50% and 100% 3RM load squats. This suggests faster squats with lower forces and slower squats with higher forces result in similar overall type II recruitment. Therefore, normalised RMS amplitude may reflect increases in number and/or firing rate of motor units, but MFCV may reflect overall proportion of type II motor units recruited (or detected) during dynamic squats. However, as power during 75% load squat was higher but MFCV was the same in comparison to 50 and 100% load levels, direct evidence of a power MFCV relationship during squats was not provided.

The findings from the maximal fatiguing squat jump showed a decrease in power as the trial progressed. The levels were defined as start, middle and end repetitions and represented increasing levels of fatigue respectively. Mean power during the concentric

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phase of the jump declined from start to middle to end repetitions, demonstrating the effectiveness of the protocol. MFCV showed a concomitant decrease, with the end repetitions showing reduced MFCV compared to start and middle. This was the expected finding, as previous research has shown MFCV to reduce with fatigue during dynamic cycling (Farina, Pozzo, *et al.*, 2004) and prolonged isometric contractions (Arendt-Nielsen *et al.*, 1989; A. M. Hunter *et al.*, 2009). It has been suggested that the cause of slower MFCV may be lower muscle pH (Brody *et al.*, 1991; A. M. Hunter *et al.*, 2009; Tesch, Komi, Jacobs, Karlsson, & Viitasalo, 1983). Reduced extracellular pH directly impairs the Na^+ K^+ pump, which results in K^+ ion accumulation in the extracellular space. This impairs polarisation and repolarisation needed for optimal action potential propagation (K. Masuda *et al.*, 1999). Although not measured, changes to muscle pH as a result of repetitive maximum effort squat jump exercise was fully expected. Therefore, this study shows MFCV reduces with significant fatigue in high intensity dynamic squat movements.

In contrast, the RMS amplitude remained unchanged across the squat jump trial. This suggests any changes in motor unit number and firing rate had no net effect upon sEMG amplitude. During sustained submaximal force tasks, sEMG amplitude increases due to additional motor unit recruitment to compensate for reduced force generation capacity (Adam & De Luca, 2005; Moritani *et al.*, 1986). The opposite occurs during sustained maximal force tasks, with decreased sEMG amplitude representing motor unit de-recruitment with fatigue (Moritani *et al.*, 1986; Taylor & Gandevia, 2008). These findings were mostly established in the isometric condition. In contrast, previous research has shown that during maximal dynamic exercise, the reduction in sEMG amplitude was less than the isometric condition (Hassani *et al.*, 2006; Kay *et al.*, 2001). This study supports specific sEMG amplitude responses during maximal dynamic contractions (Cairns *et al.*, 2005; Enoka & Duchateau, 2008; Kay *et al.*, 2000). This may be explained by previous

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findings demonstrating sEMG amplitude and force generation are disassociated during fatigue (Bigland-Ritchie *et al.*, 1983; Fuglevand & Keen, 2003). For example, the firing rates of motor units may slow during sustained contractions as a result of afferent type III and IV signalling, whilst motor unit number may increase (Enoka & Stuart, 1992). This is a NM strategy to optimise force generation known as 'muscle wisdom' (Fuglevand & Keen, 2003; Marsden *et al.*, 1983). Therefore, sEMG amplitude may be maintained, despite changes in motor unit recruitment. In contrast, MFCV reduced during the squat jump trial, indicating metabolic changes in the muscle fibres associated with peripheral fatigue. As discussed in section 3.1, direct measurement of MFCV during fatiguing contractions provides different results to frequency analysis of the sEMG signal (Farina, Pozzo, *et al.*, 2004) due to non-stationarity of sEMG signal influencing frequency variables independent of MFCV changes (Lowery *et al.*, 2002; Pozzo *et al.*, 2006). Therefore, MFCV rather than frequency variables may be informative alongside sEMG amplitude measures during NM investigations of dynamic exercise.

A technical issue arising in this study was the inability to obtain isometric MFCV values from all nine subjects. This was a result of the electrode array being displaced from the skin during the MVC tests, where maximal force led to 'bulging' of the quadriceps. These difficulties may be peculiar to well-trained and elite athlete subjects, although there was no direct evidence to support this. An alternative set up to overcome this issue is the use of a flexible electrode array. This type of array houses the electrodes within a material mould that could bend with the shape of the thigh muscles and allows the electrodes to remain in contact with the skin's surface regardless of any movement, joint angle, or muscle tone changes. However, the importance of a fixed array utilised here and in previous studies is fundamental to MFCV measurement. This is because the computation is based upon the time delay between electrodes, and so requires a constant inter-electrode distance (Farina

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& Merletti, 2004; A. M. Hunter *et al.*, 2009; Lowery *et al.*, 2002). Consequently, the use of a flexible array may lead to even less certainty as to the comparative results between load, force or fatigue conditions.

The practical difficulties for the experimenter in obtaining a MFCV measurement from all nine subjects, led to future considerations of possible methodological improvements. Firstly, the use of a smaller electrode array may allow for a more precise placement upon the muscle. This will increase the likelihood of aligning electrodes with the muscle fibres. In addition, the smaller electrode surface area is less likely to lose contact with the skin's surface during high muscle tone contractions. Secondly, the testing of the signal correlation is essential to the successful collection of reliable data and needs to be checked. The current study only tested MFCV signals from low force, seated contractions. However, it may be beneficial to assess array position and signal correlation from both seated isometric and dynamic squat contractions with high muscle tone. This may help to ensure MFCV can be obtained from all experimental conditions prior to securing the array and commencement of the trials.

3.5 Summary and Conclusion

In summary, this study established the reliability of MFCV during dynamic strength exercises, and to the researcher's knowledge, is the first to do so. The inter-trial reliability findings for the MFCV variable were acceptable for the barbell squat, but not for the squat jump. This questions whether MFCV can be analysed with confidence in fast dynamic barbell movements. Technical issues were discussed that could potentially improve the consistency in which a MFCV measurement can be successfully recorded.

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As expected, both normalised RMS amplitude and MFCV increased with isometric force. However only RMS amplitude increased with dynamic squat load. These findings suggest dynamic MFCV measurements may be less sensitive to motor unit recruitment change in response to increased load during squat exercise due to methodological issues. During fatiguing squat jumps, MFCV reduced alongside power as fatigue progressed, whilst RMS amplitude remained unchanged. This was a novel and interesting finding that suggested the net measurement of motor unit recruitment and firing rate was stable, or optimised, during fatiguing jumps. In contrast, the conduction velocity of the active units slowed, representing fatigue process occurring in the muscle. This explained the reduced power, despite the unchanged sEMG amplitude. Therefore, the combination of sEMG amplitude and MFCV provided a detailed analysis of the NM recruitment strategy and fatigue during this exercise task. In conclusion, based upon the good reliability found, direct assessment of MFCV during resistance exercise and during MVC tests may provide additional information to sEMG amplitude measurements. Consequently, the following investigations combine MFCV and RMS amplitude analysis during the resistance exercise sessions and MVC assessments performed pre and post training protocols. Specific modifications, as discussed, to the electrode array will be made to ensure robust assessment with elite athletes.

Chapter Four

Acute neuromuscular response to squat and deadlift maximum strength type training

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4. Acute neuromuscular response to squat and deadlift maximum strength type training

4.1 Introduction

Resistance exercise is used to develop athletic performance and also in clinical rehabilitation practice. Specifically, the development of maximum strength is an important outcome of resistance exercise, as it increases neuromuscular (NM) activation and cross sectional area of the muscles fibres (Aagaard, 2003; Campos *et al.*, 2002; Fry, 2004; Sale, 1988; Schoenfeld, 2010). Maximum strength training forms a key element of elite athletes' programmes due to the potential for increased force development (Aagaard *et al.*, 2002a). Recruitment of a high proportion of motor units, specifically the large type II units is important for adaptation to training (Behm, 1995). For example, greater muscle fibre recruitment has been associated with enhanced cross sectional area and force adaptations (Takarada, Takazawa, *et al.*, 2000). However, the acute NM responses that optimise chronic adaptation are not directly known and specific investigations are required to further understanding. Surface electromyography (sEMG) measures have been used to investigate NM recruitment relating to and influencing force generation during exercise (De Luca, 1997; Potvin & Bent, 1997). Specific responses are found during isometric maximal and submaximal contractions (Arendt-Nielsen *et al.*, 1989; Moritani *et al.*, 1986) and dynamic single joint tasks, such knee extensions (Hassani et al., 2006; Pincivero et al., 2006). Previous research has typically assessed single exercise bouts to fatigue, which is defined as a progressive reduction in the force or power generating capacity as a result of exercise (Cairns *et al.*, 2005; Enoka & Duchateau, 2008; Gandevia, 2001). However, few studies have analysed structured sessions of resistance exercise comprising sets of repetitions with rest intervals.

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Furthermore, little research exists investigating the NM response during dynamic multi-joint barbell exercises, commonly used by athletes and clinical patients (Stone *et al.*, 2000). Previous sEMG research shows that the type of exercise task influences NM recruitment (Maluf & Enoka, 2005). For example, greater sEMG amplitude was found during barbell versus machine squats of matched intensity (Schwanbeck *et al.*, 2009). This may influence the rate of fatigue and the degree of muscle activation that leads to the stimulus for adaptation. Differences in NM response due to barbell exercise task may relate to altered motor unit recruitment when loads are supported by the subject (Mottram *et al.*, 2005). This is possibly due to afferent signalling from the stretch reflex (type Ia) and mean arterial pressure changes (type III & IV) (Maluf & Enoka, 2005). As such the understanding of NM recruitment during multi-joint barbell resistance exercise is limited and warrants further research to help inform athletic and clinical exercise interventions. Specific understanding of differences in NM response between exercises would be of interest to provide rationale for exercise prescription.

No studies have directly compared sEMG responses between different barbell resistance exercise sessions. Smilios *et al*. (2010) demonstrated quadriceps sEMG amplitude increased over 20% during four sets of 20 squat repetitions (50% maximum load). This was associated with reduced power as the sets progressed, implying compensatory additional motor unit recruitment to maintain force generation (Arendt-Nielsen *et al.*, 1989; Moritani *et al.*, 1986). However, there was a lack of kinematic data, such as joint angle measurement, used to accurately analyse sEMG amplitude, as discussed in chapter two (Brandon, Howatson, & Hunter, 2011). Furthermore, this study was specifically designed to assess training for muscle endurance. Resistance exercise sessions for maximum strength comprise high intensity load (> 80%) and sets of two to six repetitions (ASCM, 2009; Crewther *et al.*, 2005). As NM response has been shown to vary with

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duration and intensity of contractions (Bigland-Ritchie *et al.*, 1983; Hassani *et al.*, 2006), specific investigation of maximum strength type sessions is warranted. Finally, previous sEMG studies of resistance exercise did not assess frequency spectrum or muscle fibre conduction velocity (MFCV), which may provide additional information. During sustained contractions, changes in peripheral metabolites, specifically extracellular Na^+ and K^+ ion concentrations, inhibit action potential propagation that results in reduced force generation (Cairns & Dulhunty, 1995; Fitts, 1994). These biochemical changes are reflected by a decline in MFCV (A.M. Hunter *et al.*, 2009). Chapter three showed sEMG amplitude was unchanged whilst MFCV reduced, along with power, during maximal effort squat jumps, suggesting optimisation of recruitment and firing rates to maintain power under fatigue.

The acute fatigue response to resistance exercise may also indicate the stimulus for adaptation in terms of muscle protein synthesis and neuromuscular adaptation (McCauley *et al.*, 2009). Previous studies have investigated NM fatigue using force assessment (MVC) and sEMG amplitude measured during MVC (Ahtiainen *et al.*, 2004; Hakkinen, 1994; Linnamo *et al.*, 2005). Decreased sEMG amplitude following training sessions was related to central mechanisms of fatigue and a stimulus for increased motor unit activation (Hakkinen, 1994). However, conclusions based upon sEMG data alone are limited. This is because possible changes in post-synaptic action potential propagation may reduce sEMG amplitude independent of changes in neural drive (Perrey *et al*., 2010). In contrast, repetitive dynamic plantar flexion resulted in fatigue, as shown by reduced MVC. This was associated with reduced contractile function, measured by evoked twitch force assessment (Pt), and no change in activation, measured by superimposed stimulation force (CAR) and sEMG (Klass *et al.,* 2004). This combination of findings suggests peripheral fatigue caused the reduced force generation capacity (Bigland-Ritchie, Furbush, *et al.*, 1986; Kent-Braun, 1999; Sogaard *et al.*, 2006). Few studies have investigated resistance

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exercises sessions using a combined NM assessment battery (MVC, CAR, Pt and sEMG). However, data suggests fatigue is mostly likely to be due to peripheral and not central mechanisms (Tran *et al.*, 2006), which contradicts the studies using MVC and sEMG alone (e.g. Hakkinen, 1994). In addition, no studies have specifically investigated acute NM response to sessions comprising different multi-joint barbell resistance exercises commonly utilised by elite athletes. A comparison of NM responses to the performance of ‘free-weight’ multi-joint exercises may help inform exercise prescription and training programme design. In particular, knowledge of how to plan effective training sessions without incurring fatigue would be useful, in order that other athletic training or activities of daily life following the resistance exercise are not significantly compromised.

Accordingly, the present study aims to assess the NM response during and following a maximum strength type resistance exercise session. Specifically the study compares NM response between five sets of five repetitions of either squat or deadlift exercise. There is variation in the number of sets per maximum strength session performed by elite athletes. This is dependent upon the training phase, athlete training history and whether other activities are to be performed that or the following day. However sessions involving as little as four sets are used frequently and have been shown to improve maximum strength (Hortobagyi *et al.*, 1996; Jones & Rutherford, 1987; McBride *et al.*, 2002). Importantly, the aim of the study is not to purposefully induce fatigue. Instead, the aim is to compare the response between two exercises following typical intensity, volume and rest intervals. The squat and deadlift were assessed because they are frequently included in elite athlete maximum strength programmes (see *Appendix 1*). Anecdotally, sports coaches assume different nervous system stimulus results from performing squat or deadlift, although this is not based upon research. The squat involves supporting the barbell load upon the back of the shoulders. The athlete squats down, bending at the hip and knee, and then

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concurrently extends hip and knee to return to the standing position. In contrast, the deadlift involves grasping the barbell in both hands. The barbell is lifted from the floor, with extension of the knee and hip until the athlete is upright. The weight is then released from the hand and dropped to the floor. Images of the two exercises are shown in *Appendix 2*. A recent biomechanical comparison of the squat and deadlift found different co-ordination, in terms of hip and knee joint movement (Hales *et al.*, 2009). Therefore, the two exercises are distinct tasks in term of load bearing, posture, movement and duration. The acute NM response during the exercise sessions is assessed by sEMG amplitude and MFCV measured during the sets, accurately selected from joint angles measured from an electrogoniometer. In addition, NM assessments were made prior to and following the sessions, comprised MVC, sEMG amplitude during MVC, CAR and vertical jump assessment (CMJ). The CMJ is a measure of leg extension power (Markovic, Dizdar, Jurik, & Cardinale, 2004). It was included as a specific dynamic test, involving a movement related to the squat and deadlift (Cairns *et al.*, 2005; Thorlund *et al.*, 2009).

4.1.1 Research Questions

1) What is the difference is sEMG amplitude and MFCV response during sets of squat versus deadlift exercise?

2) What is the difference in NM assessment variables pre- versus post- five sets of five repetitions of squat versus deadlift exercise session?

4.2 Methods

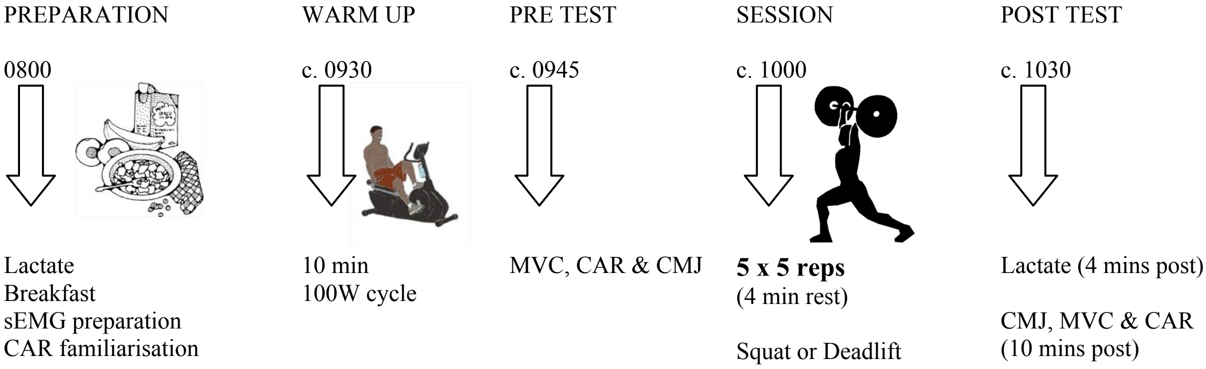

Figure 4.1. Timed summary of the squat and deadlift session procedures.

4.2.1 Subjects

Nine male subjects were actively recruited based upon their strength training skill and history. All subjects completed barbell strength training a minimum of twice weekly: Two competed in weightlifting, two were national standard javelin throwers and the remainder were professional strength and conditioning coaches, accredited by the UK Strength and Conditioning Association. Table 4.1 shows the physical characteristics of the subjects. Each subject completed a health-screening questionnaire to ascertain contraindications and provided written informed consent. The University of Stirling Sports Studies Ethics Committee approved procedures.

Table 4.1 Descriptive data of the subjects' physical characteristics.

Age (years)	Body mass (kg)	Squat load (kg)	Deadlift load (kg)	Isometric MVC knee extension force (N)
28 ± 3	86.2 ± 11.9	118.3 ± 18.0	150.6 ± 26.4	1134.9 ± 263.9

Values given as mean ± SD, n = 9. Squat and deadlift loads used during the exercise sessions are given. These correspond to a subjective rating of 17/20 (very hard) on the active muscle RPE Borg scale.

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4.2.2 Experimental Design

To establish the difference in sEMG response during, and NM responses following squat versus deadlift strength training, subjects performed either the squat or deadlift exercise sessions on two separate days, see figure 4.1. The trials were performed in a random order within seven days, with at least one rest day between each trial.

Subjects arrived at the testing centre at 0800 hrs in a fasted state and baseline blood lactate measurements were taken with the Lactate Pro device and test strips (ARK Corp, Japan). Consistency of trial times ensured any influence of circadian rhythm on NM performance was minimised (Racinais, Hue, & Blonc, 2004), including possible variation in post session responses (Bird & Tarpenning, 2004). Subjects ate a standardised breakfast comprising cereal with milk or yoghurt and a piece of fruit. Room temperature was recorded at the beginning of each trial to ensure no major differences between days existed, due to possible influence on power and MFCV (Gray *et al*., 2006; Racinais, Blonc, & Hue, 2005). Subjects' were familiarised with all procedures and the squat and deadlift loads were ascertained on a separate visit prior to the trials, see section 4.2.3.

The training session commenced at 0930 hrs with 10 minutes of ergometer cycling (Keiser M3, Keiser Corp, USA) at 100 W as a warm up. Subjects then performed the pre-session NM tests, comprising isometric knee extension force assessment (MVC), central activation ratio assessment (CAR) and a vertical jump test (CMJ), see section 4.2.5.2. The squat or deadlift exercise session was then performed. During both exercise sessions, continuous monitoring of sEMG amplitude and MFCV, barbell displacement and knee electrogoniometry measurements was made, see section 4.2.5.1. Four minutes following the completion of the final set, blood lactate samples were taken from the earlobe. The suitability of the sample timing was determined in prior pilot testing (*see Appendix 4*).

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Finally, 10 minutes following the session, CMJ, MVC and CAR tests were completed, following timings used in previous investigations of NM fatigue post cycle and strength exercise (Bentley *et al.*, 2000; Chiu *et al.*, 2004). 10 minutes was chosen to ensure the fatigue detected was not biased towards the immediate effects of the final set. As strength training is intermittent in structure, NM fatigue may vary immediately post and between sets. Assessment of NM fatigue post training needs to assess the overall fatigue resulting from the session. This has a practical significance as athletes often perform strength training followed by other training, such as technical or endurance sessions.

4.2.3 Familiarisation and Load Determination Session

Subjects attended the testing centre in a separate visit within a seven-day period prior to the trials. During which, familiarisation of the NM assessment procedures was completed. This included full instruction and practice of the MVC, CAR and CMJ assessments. For the CAR assessment, the subjects were familiarised to electrical stimulation with progressively increasing voltage whilst performing sub-maximal isometric knee extension contractions. Then subjects practised performing maximal effort isometric knee extension tests (MVC) and the voltage was superimposed during this contraction. The voltage was progressed up to the highest value subjects were able to tolerate. Recordings were made to confirm this voltage level also resulted in a measurable increase in superimposed force during the MVC (Bilodeau, 2006). This voltage level was subsequently used for the CAR assessment superimposed stimulation during the experimental trials.

In addition, the barbell loads to be used during the squat and deadlift sessions were determined. This involved performing a series of incrementally loaded sets of five repetitions, starting at a self-selected moderate load. Two to three minutes rest between sets was taken, similar to established recommendations (Baechle, 1994). At the end of

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each set, subjects rated the intensity of the load against the active muscle rating of perceived exertion (RPE), using the Borg scale (6 to 20). The trial load taken for each exercise corresponded to an active muscle RPE = 16 or 17 (very hard). The scale has been shown to be a consistent method of assessing strength exercise intensity (Gearhart *et al.*, 2001), giving exercise loads relative to maximum capabilities (Gearhart *et al.*, 2002; Lagally & Amorose, 2007). This enabled the trials to be matched for relative intensities of the squat and deadlift exercise. Whilst repetition maximum loads are normally used in resistance exercise studies, the use of active muscle RPE enables the determination of a load that is repeatable across all sets within the session. This is akin to actual methods used by elite athletes: see *Appendix 1* (question 2) for details of how coaches of elite athletes determine and progress load in training. Following recommendations to achieve rating consistency between subjects and trials (Gearhart *et al.*, 2001), subjects were given descriptions of high and low ratings, known as anchors. See *Appendix 7* for a copy of the active muscle RPE scale, with the descriptive anchors.

4.2.4 Squat and Deadlift Training Session Procedures

Figure 4.1 summarises the running order and timeline of each trial day. Following baseline measures and breakfast, subjects were prepared with a flexible electrogoniometer attached to the lateral right knee as described in detail in section 2.2.5 and a sEMG electrode array was attached over the right *vastus lateralis* muscle. For the CAR assessment, two electrical stimulation pads (4 x 8cm, Campbell Medical, UK) were attached to the proximal, medial thigh aligned over the femoral nerve and over the greater trochanter. These placements followed previous research (Lattier *et al.*, 2004; Nybo & Nielsen, 2001). They were also adopted following pilot testing because they resulted in superimposed force increments above MVC force, without the subject suffering knee pain. This was in contrast to alternative placements upon proximal and distal thigh.

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Following the cycle warm up and pre- session NM assessments, two sets of squat or deadlift were performed at light and moderate loads. This was used as a specific warm up prior to the heavy loads in the training sessions. These warm up loads were self-selected by the subjects and reflects typical practice of athletes prior to maximum strength training.

Subjects completed five sets of five repetitions of the training exercise, with four minutes rest taken between sets, using the pre-determined load (see 4.2.3). The exercises were performed with Olympic lifting barbells (Eleiko, Sweden). The squat was performed with the bar resting securely upon the top of the shoulders. The range of motion of the squat was strictly controlled, with the hips lowered to below knee level on the descent, or eccentric phase, which was performed in a controlled manner. The deadlift was performed with the barbell resting on the floor at the start of each repetition, but with subjects dropping the bar between repetitions, instead of lowering it down. Both exercises followed standard techniques used by elite athletes (H. Newton, 2006).

A metronome, emitting audio pulses at 1 Hz controlled the duration of the exercises, with subjects instructed to perform the lifting, or concentric phase over two seconds (three beeps), with as constant a tempo as possible. During each set of squat or deadlift the sEMG variables, electrogoniometer and cable-extension linear position transducer barbell displacement data were continuously recorded. Maximum knee angles following each set were checked to ensure subjects retained consistent range of motion during the sessions.

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4.2.5 Exercise repetition monitoring and NM assessment methods

4.2.5.1 Surface EMG amplitude and MFCV measurements

The following method, previously described in chapter three (A. M. Hunter et al., 2009), was used to obtain both root mean square (RMS) amplitude and MFCV from the sEMG signal. In the present study, 7.5 mm diameter Ag-AgCl shielded electrodes (EL258S, Biopac, USA) were used, and not 12.5 mm as previously. The smaller electrodes were more likely to remain in contact with the skin during high muscle tone contractions. These were inserted into a bespoke engineered hard perspex mould with an inter-electrode distance of 7.5 mm, from which four single sEMG signals were recorded and converted into three pairs of bipolar signals following (Lowery *et al.*, 2002). The four-electrode array was placed at two thirds down the line visualised from the greater trocanter to the lateral side of the patella, following SENIAM guidelines (Hermens *et al.*, 1999). This placement ensured that the electrodes were away from the motor point and distal (tendon) end of the muscle. Initially, dry silver inserts were placed into the electrode array, which was temporarily secured parallel to the approximate alignment of the *vastus lateralis* muscle fibres. Test recordings of MFCV values from seated voluntary contractions and dynamic squat contractions were obtained until the optimal array placement was determined. MFCV values were processed to confirm that this placement ensured the sEMG signals were highly correlated. These modifications to previous methodologies (A. M. Hunter *et al.*, 2009) were made to ensure both isometric MVC and dynamic exercises yielded valid MFCV measurements, as discussed in the previous chapter. The placement was then marked with permanent marker pen. The array was filled with conductive gel (20-30 µl) and securely placed using Tegaderm™ adhesive dressing (3M, USA) and additional tape. A reference (ground) electrode was placed upon the bony patella. The electrode array was linked to the Biopac MP-150 acquisition unit via bespoke sEMG amplifiers. The sEMG

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data was sampled at 2000 Hz and automatically anti-aliased and filtered using 1Hz high pass and 500 Hz low pass analogue filters, incorporated into the hardware. The RMS amplitude was processed from the raw sEMG amplitude of signal one, using a 100 ms time window, with overlapping samples. RMS amplitude values during MCV isometric knee extensions were taken as the mean RMS from a 200 ms time interval centred upon the peak force level during the MVC. The same time interval was used for processing MFCV during MVC. MFCV values were processed following previous methods in chapter three (A. M. Hunter *et al.*, 2009; Lowery *et al.*, 2002). The data from the three separate sEMG signals were first processed into two double differential signals. For accuracy, both double differential signals were up-sampled to 20 kHz to reconstruct the original un-filtered signal using Matlab software (Mathworks Inc, USA) *interpft* function. The double differential signals were then processed using the Matlab *xcorr* function. This process analysed the time delay between peaks in the two signals that were highly correlated ($r > 0.80$). In other words, identifying points from each signal that were time-delayed versions of each other, see figure 3.3. From the time delay, the MFCV is calculated as the distance between electrodes is known; where MFCV = electrode pair distance / estimated time delay.

All dynamic exercise repetition and post training session MVC RMS amplitude values were normalised to the reference RMS value captured during pre trial MVC's. Repetition normalised RMS amplitude values during the CMJ, squat and deadlift were processed from the average of the concentric phase of each movement. The MFCV value was processed from a 100 ms time interval centered on a knee angle of 70° during the concentric phase of these exercises, to limit muscle length changes that may influence MFCV values (Farina & Merletti, 2004; Kossev *et al.*, 1992). Normalised RMS amplitude and MFCV values used to describe levels of activity during squat and deadlift sets were defined as the values obtained from repetition one within sets. This is because repetition values changed across

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sets. Within-set relative repetition values were processed for normalised RMS amplitude and MFCV, with respect to repetition one of each set. For simplicity normalised RMS amplitude is referred to as RMS in the following text.

4.2.5.2 MVC, CAR and CMJ assessments

The subjects performed the knee extension MVC force and CAR test as one combined assessment, using a dynamometer machine (Kin Com, Chattanooga, US). The MVC procedures followed previous methods (J. L. Andersen & Aagaard, 2000; Hortobagyi *et al.*, 1996). Subjects were strapped with a waist and shoulder harness into a seat, which was reclined at 15°. The hip angle was 90° and the knee flexion angle was 70°, with respect to 0° corresponding to a fully extended knee. Previous research has established that MVC assessment performed with a knee angle of 70° results in both peak force and voluntary activation values (Becker & Awiszus, 2001; Pincivero *et al.*, 2004). The seat position was adjusted for each subject so that lateral epicondyle of the knee joint was visually aligned to the rotational axis of the dynamometer. The length of the dynamometer's lever arm was individually adjusted so that the ankle attachment was firmly secured to the subjects' shank, just above the medial malleolus.

Subjects performed a series of warm up contractions, with increasing intensity. Subjects were instructed to slowly build up to maximal force and verbally encouraged to exert maximal effort. The trial MVC's were maintained for eight seconds, to allow for the slow progression of force, with 60 s rest between test contractions. A visual target on the dynamometer display screen was provided and immediate feedback of performance given to enhance voluntary effort and reliability, as recommended by Gandevia (2001). Each subject performed three maximal effort MVC trials. The trial resulting in the best peak force value was taken to represent MVC force. Peak force was processed as the mean

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value from a 200 ms interval centred upon the peak force value. The same 200 ms interval was used to process RMS from the sEMG recording and was also subsequently used as the reference RMS value for normalisation.

The CAR assessment occurred during one of the MVC trials, chosen at random and without warning. Subjects were percutaneously stimulated with a stimulator device (StimISOC, Biopac Systems Inc, USA) with a 250 ms 100 Hz titanic pulse train (Nybo & Nielsen, 2001). The voltage used was pre-determined during the familiarisation session (see above 4.2.3). The stimulation occurred six seconds into MVC test, with subjects instructed and coached to build up to and maintain consistent force levels during the stimulation (Kent-Braun & Le Blanc, 1996). To obtain the CAR value two force values were obtained, the peak force value force prior to the stimulation and the peak force value during the stimulation. From this, CAR = (MVC force / superimposed stimulated force) x 100, following previous methods (Kent-Braun & Le Blanc, 1996; Nybo & Nielsen, 2001).

Three maximal counter movement jumps (CMJ) were performed with a 30 s pause between each. Subjects held a wooden stick upon their shoulders during the performance of the jump to remove the any variability in the use of the arms (Markovic *et al.*, 2004). The wooden stick also enabled a cable-extension linear position transducer device (Celesco PT5A, USA) to directly measure jump height displacement. The free end of the cable was securely attached to the left hand side of the stick. The device itself was placed upon the floor, visually aligned to the subjects left ankle and hip. This set up ensured that the cable ran as vertically as possible. Subjects were instructed to jump as high as possible, maintaining a straight and vertical body position in the air and landing back in the same place. This technique minimised horizontal movement during the jump. CMJ assessment height was processed directly as the difference between the displacement measured at

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standing height prior to the jump and displacement at the peak height of the jump, following previous position transducer methods (Cormie *et al.*, 2010b; Nuzzo, McBride, Cormie, & McCaulley, 2008). The mean of the three CMJ height values was taken.

4.2.5.3 Squat and deadlift biomechanical measures

Barbell displacement was measured during squat and deadlift repetitions. The same cable-extension linear position transducer device (Celesco PT5A, USA) as the CMJ was used. The free end of the cable was securely attached to the left hand side of the barbell and the device itself was placed upon the floor, visually aligned to the subjects left ankle and hip. This set up ensured that the cable ran as vertically as possible during the squat and deadlift. The displacement data was used to estimate mean power during the concentric phase of each exercise, following previous methods (Cormie, Deane, *et al.*, 2007; Dugan *et al.*, 2004). Findings from chapter two showed these methods to be reliable (Brandon et al., 2011). The mean power data provided a description of the performance of each repetition (Bosco *et al.*, 2000, Cairns *et al.* 2005). Filtered displacement data was processed into power using the recording system's software functions (AcqKnowledge ® 3.8.1, Biopac Systems Inc., Santa Barbara, CA). Displacement data was derived into velocity and then acceleration using the time data from the sample rate: (Velocity = Δdisplacement/Δtime, then, Acceleration = Δvelocity/Δtime.) Acceleration was then converted into vertical force as the product of system mass and the acceleration of the system plus the acceleration due to gravity. Finally, power was determined as the product of force and velocity at each time point: (Force = System mass x (Acceleration + 9.812), then, Power = Force x Velocity.)

Knee angle data from the flexible electrogoniometer was also measured during squat and deadlift repetitions, following methods established as reliable in chapter two (Brandon et al., 2011). The measurement of knee angles was used to control range of motion during

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the exercises, ensuring consistent exercise technique throughout the training sessions. Importantly, the electrogoniometer allowed for precise determination of the beginning and end of the concentric phase of the squat, deadlift and CMJ. Thereby ensuring consistency of the period from which mean power, RMS and MFCV values were processed between subjects and across sessions. The software's screen functions (AcqKnowledge ® 3.8.1, Biopac Systems Inc., Santa Barbara, CA) were used to determine the start of the concentric phase as the point of maximum knee angle (point of maximal flexion) corresponded to the point where displacement started to increase positively. The end of the concentric phase was when the knee returned to 0°, or fully extended (see figure 2.5). Specifically, for the deadlift the concentric phase was defined as starting 200 ms post the positive rise in displacement. This was when the bar had just been lifted off the floor, and enabled the mass of the barbell and lifter to be treated as one mechanical system. The displacement and mean velocity values used for the mean power calculation were also recorded for comparison between exercises. Relative mean power, with respect to repetition one of each set, were also processed. This was used to compare changes in power within sets during each exercise session.

The time period of the concentric phase was also used to define repetition duration of the deadlift. In contrast, the repetition duration of the squat was defined as difference in time from where knee angle began at 0° (fully extended) and displacement started to decrease and the time point at the end of the concentric phase when the knee returned to 0°. Repetition duration corresponds to the time of the movement. This is simpler to define than time under tension, which implies muscle activity, and may occur without movement during strength exercises. From the repetition duration and derived force values, impulse was calculated as the integral of force over time. Maximum knee angles, repetition duration and impulse values were obtained for all repetitions of squat and deadlift using the

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analysis system's software functions. Mean set values from the average of the five repetitions from each set were obtained for concentric mean power, repetition duration, impulse and maximum knee angle, bar displacement and mean velocity.

4.2.6 Statistical methods and analysis

Descriptive statistics (mean ± SD) for RMS, MFCV, mean power, impulse, repetition duration, maximum knee angle, bar displacement and mean velocity were completed. Mean ± SD pre and post values for lactate, MVC, CAR, CMJ height, RMS during MVC, MFCV during MVC and RMS during CMJ were also provided. Changes in repetition RMS and mean power within sets of squat and deadlift were assessed using a three-factor repeated measures ANOVA test (repetition x set x session). Differences between and within training sessions in repetition RMS and mean power were assessed using a two factor repeated measures ANOVA test (session x set). Differences between sessions and between times (pre v post) for MVC, RMS during MVC, CAR, CMJ, RMS during CMJ and Lactate were assessed using a two factor repeated measures ANOVA (session x time). Significant main effects were followed by *post-hoc* Tukey's tests. One-way ANOVA was used to compare exercises session differences of the mechanical variables and relative change in MFCV between 1st and 5th repetition for all sets combined. Statistical significance was accepted at $p<0.05$. Statistics were performed using Minitab 15 software (USA), which reports statistics to nearest three decimal places.

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4.3 Results

The results compare the two training sessions performed with the different exercises. These are referred to as squat session, deadlift session, or collectively as exercise sessions.

4.3.1 Mechanical description of squat and deadlift sessions

The mechanical data describes each exercise and demonstrates the effectiveness of the controls used in the study. Table 4.2 describes the significantly greater impulse ($F = 41.80$, $p<0.001$), repetition duration ($F = 93.6$, $p<0.001$) and maximum knee angle ($F = 8.74$, $p<0.001$) found during squat session compared to deadlift session. Bar displacement and mean velocity were not different between exercise sessions. Mean power was significantly higher during the deadlift session compared to squat session across all sets ($F = 13.20$, $p = 0.007$), see figure 4.2. As velocity was similar, this difference was a result of greater load used during deadlift compared to squat, 150.6 ± 26.4 versus 118.3 ± 18.0 kg respectively ($t = 6.82$, $p<0.001$). There was no difference in mean power between sets during either exercise session. In addition, mean power within sets was unchanged, expressed relative to repetition one of each set.

Table 4.2. Mechanical descriptors of squat and deadlift exercise sessions.

	Impulse (N.s)	Repetition Duration (s)	Displacement (m)	Mean Velocity ($m.s^{-1}$)	Maximum Knee Angle (°)
Squat	6814 ± 1331**	3.7 ± 0.4**	0.58 ± 0.03	0.34 ± 0.02	123.0 ± 10.9**
Deadlift	3512 ± 758	1.7 ± 0.2	0.59 ± 0.05	0.36 ± 0.03	106.6 ± 10.2

Values are combined mean ± SD for all sets, n = 9. ** Significant difference between exercise sessions, p<0.001.

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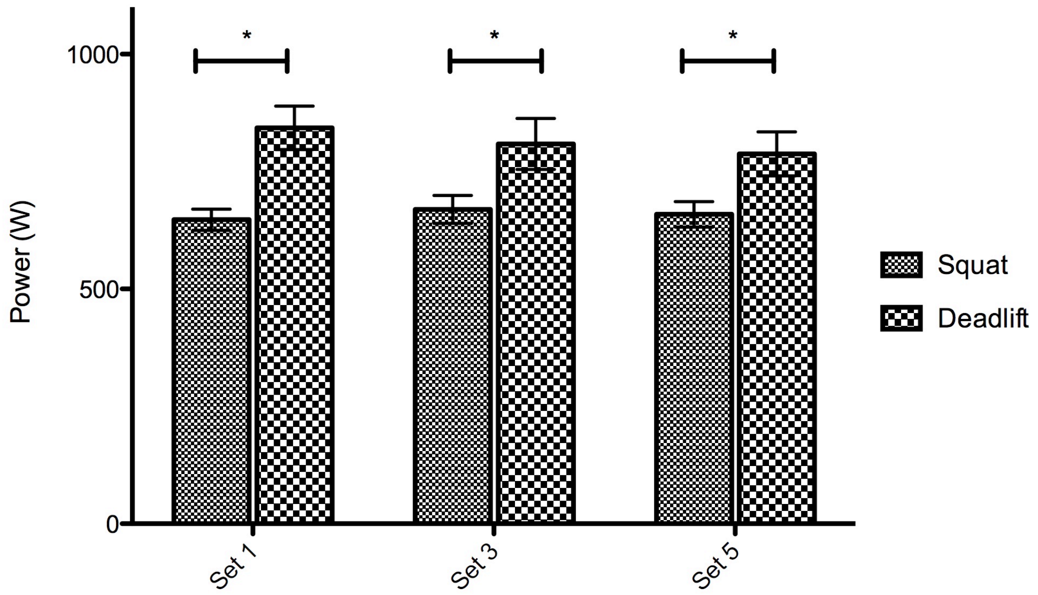

Figure 4.2. Mean power during the concentric phase of squat and deadlift sessions.
Mean ± SD power during sets 1, 3 & 5 for squat and deadlift were 647.6 ± 67.9, 669.6 ± 88.8 & and 659.1 ± 81.4 W and 843.0 ± 138.7, 808.7 ± 163.1& 787.7 ± 140.5 W respectively, n = 9. * Significant difference between sessions for all sets, p<0.01. No different between sets during either exercise session.

4.3.2 RMS and MFCV findings during the sessions

Normalised RMS amplitude (RMS) and MFCV values were not different between exercise sessions. There was also no difference in RMS or MFCV between sets during either exercise session. The results are described in Table 4.3.

Table 4.3 RMS and MFCV data during sets 1, 3 and 5 of squat and deadlift sessions.

	RMS (%)		MFCV ($m.s^{-1}$)	
	Squat (n = 9)	Deadlift (n = 9)	Squat (n = 5)	Deadlift (n = 7)
Set 1	83.4 ± 35.5	84.3 ± 36.0	2.87 ± 0.91	3.22 ± 1.13
Set 3	79.3 ± 36.4	76.4 ± 36.8	2.87 ± 0.91	3.27 ± 1.35
Set 5	72.8 ± 39.6	79.4 ± 37.3	2.78 ± 0.82	3.17 ± 0.98

Values are given as mean ± SD. RMS values were normalised relative to RMS during pre-session MVC.

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Figure 4.3 describes the significant increases in RMS (F = 33.80, p<0.001), expressed relative to repetition one, during sets of both exercise sessions. In addition, there was a significant session by set interaction (F = 20.40, p<0.001) and significant session by repetition interaction (F = 2.34, p=0.022). *Post hoc* tests revealed the following: Repetitions two to five were all significantly higher than repetition one during sets of the squat session. In contrast, repetitions four and five were significantly higher than repetition one during sets of the deadlift session. Additionally, within the squat session, RMS (relative to repetition one) during set five was greater than sets one and three. Within the deadlift session, RMS was greater during set three compared to sets one and five.

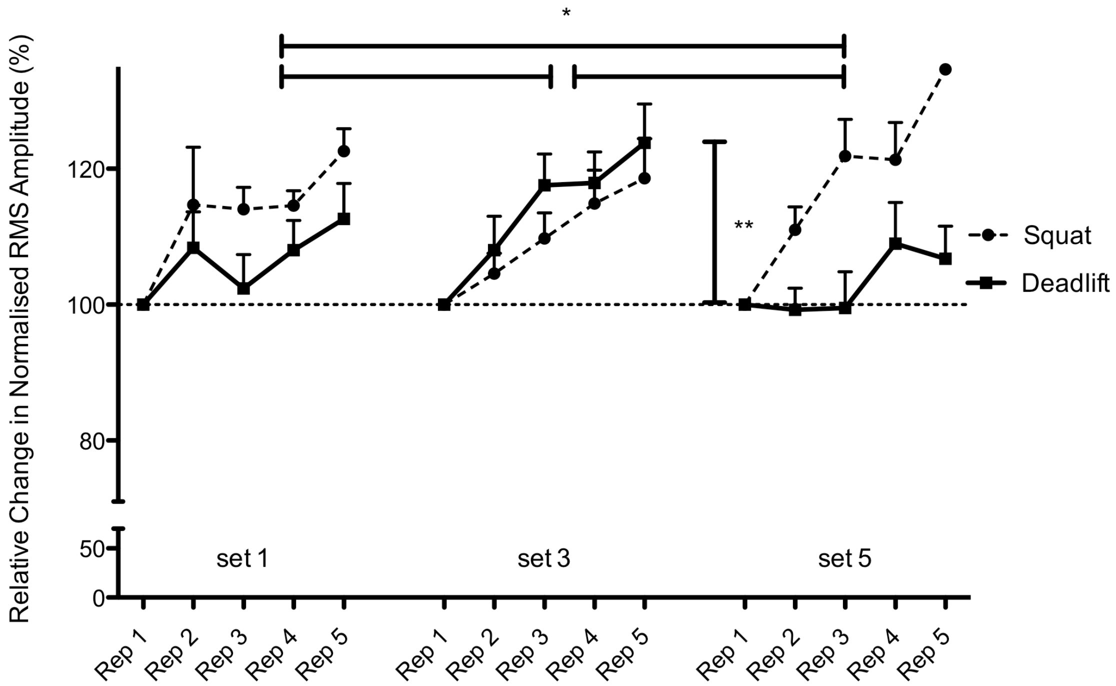

Figure 4.3. Relative repetition RMS amplitude within sets of squat and deadlift.
Mean values are given relative to repetition one for each set, n = 9. * Significant interaction effect between session by set and session by repetition, p<0.05, and ** significant difference between repetitions within sets during both exercise sessions, p<0.001.

Figure 4.4 illustrates the change in MFCV, expressed relative to repetition one, during sets squat session (F = 4.91, p = 0.034), but not within sets of deadlift session. All sets were combined for the analysis. Repetition MFCV values were obtained from only five subjects in both squat and deadlift sessions.

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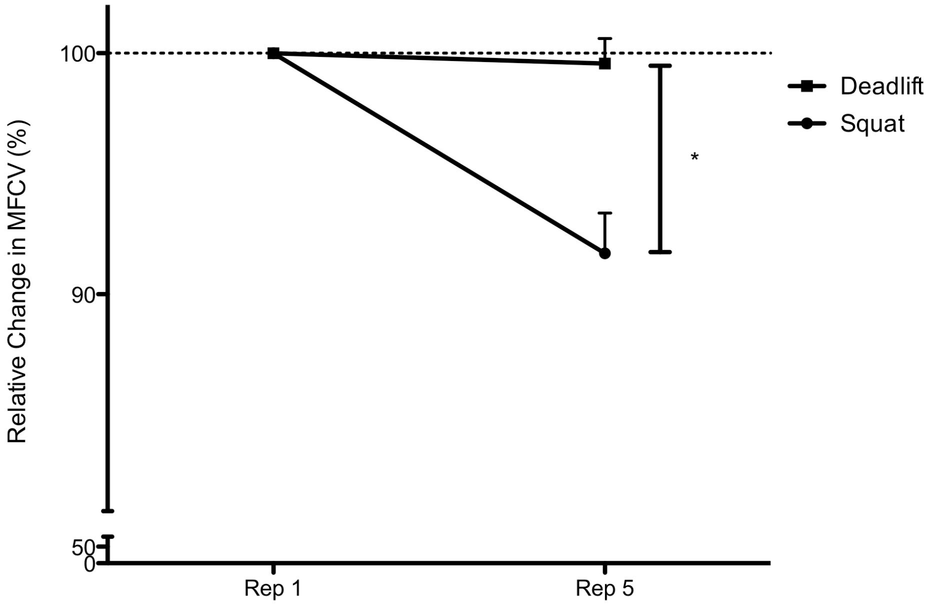

Figure 4.4. Relative MFCV for repetition five during sets of squat and deadlift.
Repetition five mean ± SD values, n = 5, are given relative to repetition one and combined for all sets. * Significant difference between sessions, p<0.05.

4.3.3 Pre versus Post Neuromuscular & Lactate assessments

Table 4.4 describes the NM assessment variables pre and 10-minutes post both exercise sessions. There were no differences in any pre- assessment values between squat session and deadlift session. There were also no differences between pre- and post- session assessment values. In other words, all NM assessments were unchanged following both exercise sessions. However, there was a significant interaction effect for session by time for MVC ($F = 5.90$, $p = 0.041$), see figure 4.5. *Post hoc* tests revealed MVC post- squat session showed a tendency to be lower than MVC post- deadlift session ($p = 0.06$ with CI = -8.6 to 113.7N). Lactate was significantly higher following both exercise sessions ($F = 49.84$, $p<0.001$). There were no differences between exercise sessions, baseline or post-session. Baseline lactate values were 1.1 ± 0.1 and 1.0 ± 0.1 $mmol.L^{-1}$ and post-session values were 3.79 ± 1.6 and 4.1 ± 1.9 $mmol.L^{-1}$ for squat session and deadlift session respectively.

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Table 4.4. Pre- versus post- squat and deadlift session values for MVC, RMS during MVC, MFCV during MVC, CAR and CMJ.

		Squat	Deadlift
MVC (N)	pre	1135 ± 264	1122 ± 225
	post	1093 ± 264 $	1147 ± 252 $
RMS during MVC (%)	pre	100 ± 0	100 ± 0
	post	99 ± 16.2	108 ± 36.7
MFCV during MVC ($m.s^{-1}$)	pre	2.67 ± 0.98	2.62 ± 0.57
	post	2.32 ± 0.73	2.58 ± 0.67
CAR (%)	pre	96.2 ± 1.8	96.3 ± 2.3
	post	95.5 ± 1.3	95.8 ± 3.8
CMJ Height (cm)	pre	45.0 ± 2.9	45.6 ± 2.9
	post	44.8 ± 3.0	46.6 ± 1.9

Values are given as mean ± SD, n = 9 for all assessment values, except MFCV where n = 5 for squat and n = 7 for deadlift. $ Significant interaction effect for MVC between session and time, p<0.05.

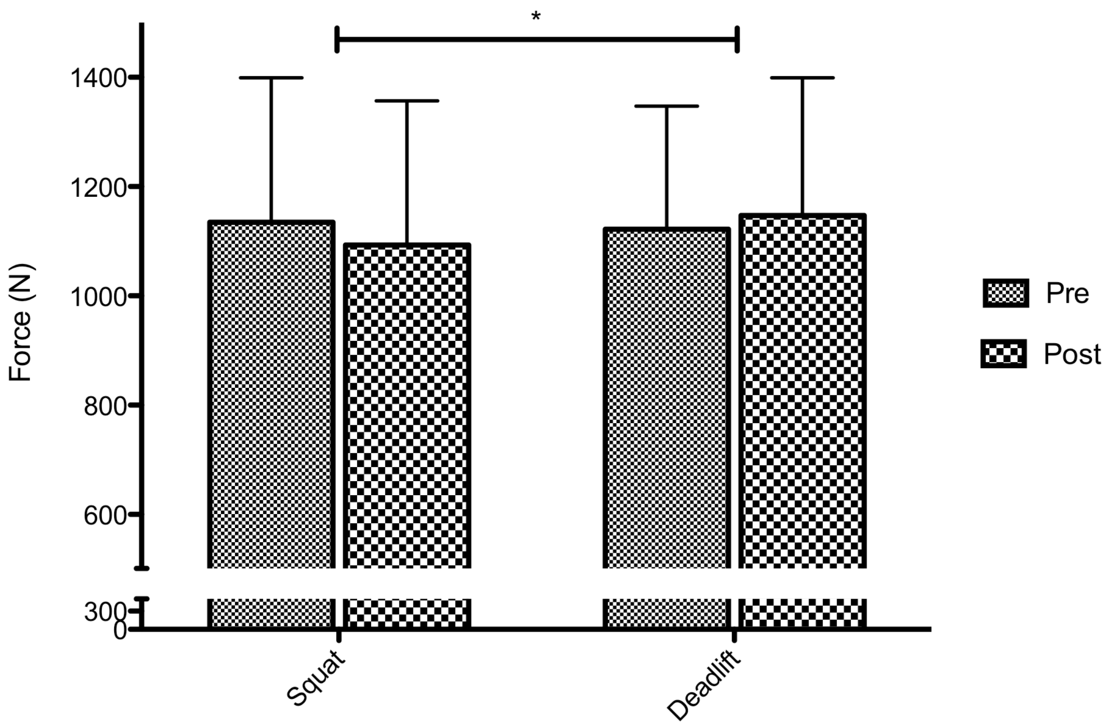

Figure 4.5. MVC values pre and post squat and deadlift sessions.
Values given as mean ± SD, n = 9. * Significant interaction between session and time, p = 0.041.

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4.4 Discussion

The study compared the NM response to maximum strength type resistance exercise sessions between two different multi-joint barbell exercise tasks. Maximum strength sessions are defined as a specific volume (sets x repetitions) and intensity of resistance exercises in order to improve this physical quality (ASCM, 2009). This is distinct from maximal intensity dynamic contractions, performed to fatigue in other NM investigations.

Specific control methods were utilised to ensure differences in NM response between sessions was due to differences in the task and not exercise performance. Both exercises involved similar bar displacement and mean velocity during the concentric (lifting) phase. However, the squat also involved an eccentric (lowering) phase. Hence the significantly greater impulse and repetition duration found. This suggests greater work was performed during squat. The greater mean power during deadlift exercise is a result of the greater load lifted with a similar velocity. Importantly, subjects adhered to the metronome pacing throughout the sessions. Consequently, there was no change in repetition mean power during the exercise sets. Therefore, no fatigue in exercise performance was observed. The squat and deadlift RMS values were similar, suggesting comparable levels of quadriceps motor unit recruitment and/or firing rates. This supports the use of the active muscle RPE method of matching intensity between resistance exercises (Pincivero, Coelho, & Erikson, 2000). Altogether, these data show that the subjects were able to perform the exercises as intended and exercise performance was comparable between sessions, despite clear exercise task differences.

The key finding was RMS increased during both exercise sessions, whilst MFCV was sustained and reduced in deadlift and squat sessions respectively. Increased RMS reflects increased neural drive leading to greater discharge, or firing rates detected in the sEMG

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signal (Enoka & Stuart, 1992; Gandevia, 2001). Increases in RMS following a period of sustained force production may reflect a NM strategy to maintain force generation via additional motor unit recruitment, often interpreted as submaximal peripheral fatigue (Sogaard *et al.,* 2006*)*. Increased RMS may also reflect the demands of the task, independent of fatigue processes. For example, maintaining load and position results in fast increases in motor unit recruitment (Mottram *et al.*, 2005), due to afferent feedback mechanisms, such as the stretch reflex. Changes in MFCV reflect the balance between overall recruitment and the fatigue occurring within the active motor units (Arendt-Nielsen *et al.*, 1989). The latter is probably due to metabolite accumulation disrupting action potential propagation, specifically a lowering of pH, which will affect Na^+ and K^+ ion balance in the extracellular space (A. M. Hunter *et al.*, 2009; K. Masuda *et al.*, 1999). The combination of reduced MFCV and increased RMS during sets of squat exercise suggests that peripheral submaximal fatigue occurred. RMS increased at a greater rate during sets of squats, as repetitions two through five were greater then repetition one, whilst only repetitions four and five were greater than repetition one during sets of deadlift. In addition, the repetition RMS was greater during set five of squat session, suggesting greater additional motor unit recruitment as the session progressed. Perhaps the longer repetition duration of squat exercise led to greater peripheral metabolic changes, reflected in reduced MFCV. This may have resulted in afferent type III and IV signalling to increase motor unit recruitment in compensation for slower firing rates (Enoka & Stuart, 1992; Maluf & Enoka, 2005). In contrast, the finding of unchanged MFCV with increased RMS during deadlift session is best explained as increased motor unit recruitment in response to task, independent of submaximal peripheral fatigue. Interestingly, there was no difference between the post session blood lactate responses. However, whole body blood lactate measurement can be insensitive to detecting metabolic differences in the quadriceps (A. M. Hunter *et al.*, 2009).

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These findings are interesting as increased motor unit recruitment during sets of maximal strength type multi-joint barbell exercises may provide a stimulus for NM adaptation (Ahtiainen & Hakkinen, 2009; Gonzalez-Izal *et al.*, 2010; Pincivero *et al.*, 2006). However, this study suggests this stimulus may occur independent of fatigue, as the performance of the resistance exercises (repetition power) was maintained. In addition, the increased activation may also occur independent of acute peripheral fatigue processes that were indicated by MFCV, as occurred during deadlift. However, acute peripheral fatigue may increase motor unit recruitment further, as shown during squat. Importantly, the findings are not consistent with previously studied sEMG responses of dynamic maximal contractions. These investigations tend to show either reduced sEMG amplitude (Hassani *et al.*, 2006) or little change (Kay *et al.*, 2000), such as finding from chapter 3 during maximal squat jump trials. This suggests that resistance exercise sessions designed to improve maximum strength, do not necessarily involve maximal contractions performed until fatigue. This is significant, as sports coaches tend to assume reduced NM activation results from maximum strength type sessions.

Unfortunately, the present MFCV findings were confounded by only obtaining measurements from five and seven subjects (out of nine), during squat and deadlift respectively. The researcher acknowledges the difficulty in the preparation and placement of the electrode array in order to obtain a correlated signal during dynamic contractions. This is likely due to relative movement of the electrode array with respect to muscle fibre alignment and muscle length changes (Farina *et al.*, 2006; Kossev *et al.*, 1992).

The study also compared pre- and post- exercise session NM assessments, with no difference found between squat and deadlift sessions. This suggests a structured session comprising five sets of squat or deadlift exercise, and four minutes rest between, did not

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influence force generation capacity or central activation, as assessed by MVC and CAR (Klass *et al*., 2004). Specifically, CAR represents the central activation of the muscle, related to motor neuron excitation and firing rate (Taylor & Gandevia, 2008). This is useful information for coaches and athletes, as well-trained subjects may perform five sets of resistance exercise, which is proven to provide effective stimulus to develop maximum strength (Hortobagyi *et al.*, 1996; Jones & Rutherford, 1987; McBride *et al.*, 2002), without detriment to other kinds of training. This is important for elite athletes who train multiple physical and technical areas, often within the same day. Interestingly, these findings also suggest the stimulus for NM adaptation is not dependent upon decreased neural activation following resistance exercise sessions. Whilst no overall changes were found, an interaction between session and time was found for MVC force assessment (see figure 4.5). In fact, six out of the nine subjects increased MVC force post- deadlift session whereas eight subjects reduced MVC post- squat session. A possible explanation is the deadlift session comprised an optimal combination of intensity and duration to result in a positive warm up rather than fatigue effect. This is perhaps reflected by the difference in exercise impulse, although this was not directly assessed. Further discussion of this interaction effect can be found in *Appendix* 5.

Lack of observed change in NM assessment contrasts previous studies involving high volume sessions that found reduced MVC and sEMG amplitude during MVC post-session (Ahtiainen & Hakkinen, 2009; Hakkinen, 1994; Linnamo *et al.*, 2005). This is likely due to greater session volume than the present study (4 - 10 sets of 10 - 12 repetitions). These previous studies also measured MVC and sEMG amplitude immediately following the final set, which may also account for differences found. The immediate effects of the repetitions, such as ischemia or muscle pH changes, may influence action potential propagation, and subsequent contractile function which influence both MVC and sEMG

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amplitude measures (Fitts, 1994). This may bias the findings towards the acute changes of the final set and not the impact of the entire session. Temporary alterations in sEMG amplitude following fatiguing contractions may recover within minutes (Gandevia, 2001). Therefore, 10 minutes was selected to ensure total session, and not final set, NM function was assessed, following previous investigation timings (Chui *et al.*, 2004). The assessment of NM fatigue resulting from the entire session informs coaches and athletes of muscle function changes that may influence the performance of other training.

It is acknowledged that this study used active muscle RPE to determine loads, instead of the more widely used repetition maximum (RM) method. The RM method directly matches load based upon the number of possible repetitions that can be performed. The active muscle RPE method is based upon subjective ratings. However, RMS data supported the fact that exercises in this study involved comparable intensity (Pincivero *et al.* 2000). The disadvantage of using RM loads is that a reduction in load occurs as the session progresses; otherwise it would be impossible to perform the target number of repetitions. For example, 100kg for 5RM during set one may reduce to 80kg for 5RM in set five. This is not representative of how elite athletes train during maximum strength sessions (see *Appendix 1).* As explained in section 4.2.3, active muscle RPE allows the loads to be repeatable across each set of the exercise sessions, and to be comparable between sessions and subjects (Gearhart *et al.*, 2002; Gearhart *et al.*, 2001).

A further limitation of the present methods was the reliance upon analysis of sEMG and force from a single muscle group, namely the quadriceps. It is possible that fatigue may vary between muscle groups involved in whole body movements such as squat and deadlift. For example, assessment of knee extension MVC force and quadriceps sEMG response may not accurately represent muscle function change at the hip and trunk.

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Technical differences between the deadlift and squat exercise may influence fatigue occurring in different muscles. However, biomechanical analysis of barbell squat found higher knee extensor moment, compared to the hip joint (Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001; Fry *et al.*, 2003). This is evidence that the knee joint is performing a significant amount of work during the squat exercise, with high muscle activation levels (Wretenberg *et al.*, 1996). In addition, the body of literature of multi-joint resistance exercises and other applied exercise research has used quadriceps sEMG and knee extension MVC force as fatigue measurements (Drinkwater *et al.*, 2009; Hakkinen, 1993, 1994; A. M. Hunter *et al.*, 2009; Thorlund *et al.*, 2008). Therefore, despite possible limitations, the assessment methods used presently were considered appropriate.

4.5 Summary and Conclusion

In summary, RMS increased during sets of both squat and deadlift sessions, whilst MFCV reduced only during sets of squat session. This NM response may reflect additional motor unit recruitment to achieve the maintained power during the lifting of the loads. This is typical of sEMG responses in sustained sub-maximal contractions. However, acute peripheral fatigue was more likely to have occurred during sets of the squat and not deadlift exercise, indicated by reduced MFCV. Therefore, increased RMS may result simply due to repetition of the exercise tasks (Maluf & Enoka, 2005), with or without fatigue. There was no change in NM assessments following either exercise session, suggesting maximal strength type sessions comprising five sets of multi-joint barbell exercise does not significantly affect force generation capacity. This allows maximum strength sessions to be performed with other training activities. The findings suggest the stimulus for training adaptation is the increased motor unit activation during the exercise repetitions, independent of fatigue. This would lead to recruitment of large type II muscle fibres, helping promote long-term gain in maximum strength. However, further research is warranted to understand this in greater detail.

Chapter Five

Comparison of the neuromuscular response and 24-hour recovery between maximum strength and power sessions in elite male and female athletes

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5. Comparison of the neuromuscular response and 24-hour recovery between maximum strength and power sessions in elite male and female athletes.

5.1 Introduction

Athletes use specific types of resistance exercise to develop different physical qualities. Sessions comprising high intensity (> 80% maximum load) and low repetitions (two to six) are performed to develop maximum strength (ASCM, 2009; Crewther *et al.*, 2005). Sessions comprising low load exercises performed with high velocity are performed to develop power (McBride *et al.*, 2002; Moss *et al.*, 1997; Wilson *et al.*, 1993). Physiological adaptations to maximum strength training involve increased muscle fibre cross sectional area (L. L. Andersen *et al.*, 2005; Jones & Rutherford, 1987) and increased neural drive (Aagaard *et al.*, 2002a). Power type training also improves neural drive, particularly rapid motor unit activation (Van Cutsem *et al.*, 1998), and increased ability to generate force during dynamic high velocity movements (Cormie *et al.*, 2010a; Moss *et al.*, 1997; R. U. Newton *et al.*, 1999). Therefore, the adaptations following resistance exercise occur in both peripheral and central sites of the neuromuscular (NM) system, and are specific to the training performed.

Previous research has shown the contribution of peripheral and/or central NM system to fatigue varies as a result of exercise intensity (Yoon *et al.*, 2007), duration (Behm & St-Pierre, 1997; Sogaard *et al.*, 2006) and type of contraction (Babault *et al.*, 2006). Peripheral fatigue is defined as reduced force generation by the muscle arising distal to the neuromuscular junction, and may include reduced action potentiation propagation, excitation-contraction coupling, and metabolite accumulation (Bigland-Ritchie, Furbush, *et al.*, 1986; Fitts, 1994). Peripheral fatigue is indicated by reduced isometric maximal force

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(MVC) combined with reduced evoked peak twitch force (Pt) assessments (Bigland-Ritchie, Cafarelli, *et al.*, 1986). MVC represents the force generation capacity of the whole neuromuscular system (Gandeiva, 2001), whilst Pt represents the contractile status of the muscle, peripheral to the neuromuscular junction (Fowles & Green, 2003). Central fatigue is defined as a fatigue response resulting in reduced motor unit activation (Babault *et al.*, 2006) arising proximal to the neuromuscular junction. This is indicated by changes to the stimulated force superimposed on a MVC assessment (CAR) (Kent-Braun, 1999). The CAR assessment represent changes in motor neuron firing rates due to changes in efferent drive and/or afferent feedback (Taylor & Gandevia, 2008). Using these measures Klass *et al.* (2004) examined the effects of a single bout of repetitive moderate force dynamic contractions, which resulted in reduced maximal force generation. The authors concluded this reduction was related to peripheral fatigue mechanisms, based upon reduced Pt but not CAR measures (Klass *et al.*, 2004). Sessions of resistance exercise comprise dynamic repetitions, structured intermittently into sets interspersed with rest periods. The methods used to investigate single bouts of exercise may also inform possible variation in NM response between resistance exercise sessions of different intensity, volume and contraction velocity.

Previous research has studied NM fatigue and recovery using MVC and surface electromyography (sEMG) following very high intensity (20 x 1RM) (Hakkinen, 1993) and high volume (10 x 10RM) resistance exercise sessions (Hakkinen, 1994). The studies found significant decreases in MVC force for male and female subjects immediately following the sessions, along with incomplete recovery 24-hours post-session. This was associated with reduced sEMG amplitude, representing motor unit activation. From this they concluded peripheral and central fatigue had occurred, with greater peripheral fatigue in males due to greater loss in force and increase lactate post the high volume session.

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However, conclusions based upon sEMG measurements alone are limited due to possible peripheral changes in post-synaptic action potential propagation rates that may alter sEMG amplitude independent of changes in neural drive (Perrey *et al.*, 2010). A previous comparative study of high volume strength and high velocity power type resistance exercise sessions found significantly greater fatigue following the strength type session (Linnamo *et al.*, 2005). The findings suggested central fatigue was more significant following power type session, as lactate was not increased but sEMG amplitude reduced. However, this conclusion was based upon indirect evidence of central and peripheral fatigue. Previous investigations that used MVC, Pt, CAR and sEMG assessments found no evidence of central fatigue mechanisms following elbow flexion resistance exercise sessions (Behm *et al.*, 2002; Tran *et al.*, 2006). Therefore, understanding of NM fatigue following maximum strength and power resistance exercise sessions, and possible gender differences, are unclear due to different methodologies used.

A better understanding of the NM response following maximum strength and power resistance exercise may inform training programme planning to optimise adaptation. Peripheral fatigue may indicate a stimulus for cross section area adaptation (McDonagh & Davies, 1984; Schoenfeld, 2010), whereas central fatigue may indicate nervous system stimulus for optimisation of motor unit recruitment (Hakkinen, 1994). In addition, as chapter four demonstrated, increased sEMG amplitude during sets of maximum strength type resistance exercise indicates greater motor unit recruitment, thereby providing NM stimulus for adaptation (Ahtiainen & Hakkinen, 2009; Gonzalez-Izal *et al.*, 2010; Pincivero *et al.*, 2006). Additionally, the degree and nature of fatigue will determine the recovery time required, influencing the type of physical or technical training that is suitable following, or in conjunction with resistance exercise. For example, knowledge of NM function 24-hours following maximum strength and power type resistance exercise may

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help coaches plan consecutive day sessions, as multiple types of training occur across the week. Therefore, the first and primary purpose of this study was to compare the acute NM response and 24-hour recovery between maximum strength and power type resistance exercise sessions. The second aim was to compare male and female responses within a subject group of elite athletes. This may help inform whether elite male and female athletes respond differently to maximum strength and power type sessions.

To add to the literature, and ensure the findings are relevant to an elite athlete population, the present study investigates a specific structure and volume of maximum strength and power resistance exercise session. The sessions comprise a series of three exercises, four sets of five repetitions per exercise, interspersed with three minutes rest between sets. The previous chapter found no change in force generation following five sets of maximum strength type training. However, when elite athletes are prioritising maximum strength and power development, sessions typically involve more than 10 sets and multiple exercises (J. L. Andersen & Aagaard, 2000; Campos *et al.*, 2002). Consequently, the present study assesses a volume of training that is likely to induce NM fatigue. In addition, the present study assesses Olympic-style barbell exercises, which also represents elite training methods (see *Appendix 1).* The previous comparison of strength versus power type sessions involved machine exercise (Linnamo *et al.*, 1998). However, analysis of free-weight exercises is warranted, as differences in muscle activation levels in barbell versus machine exercises has been shown (Schwanbeck *et al.*, 2009). Finally, an elite group of subjects was proactively recruited to ensure high quality training session execution. NM responses to resistance exercise have been shown to be greater in strength-trained athletes (Ahtiainen & Hakkinen, 2009). This is related to an increased ability to tolerate training (Fry *et al.*, 1994) and increased neuromuscular recruitment and co-ordination (Aagaard, 2003; Aagaard *et al.*, 2002a; Hakkinen *et al.*, 1998).

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The present study follows the methodology used in chapter four, with specific additions. NM assessments were made pre- and post- maximum strength and power sessions. This comprised MVC, sEMG amplitude during MVC, Pt, CAR and vertical jump (CMJ). 24-hour measures of MVC, CAR and CMJ were also taken. As stated, Pt is a measure of a contractile function of the muscle and is associated with the excitation contraction coupling process (Hill *et al.*, 2001). In comparison to other variables, such as rate of twitch development, Pt is less likely to be influenced by possible post-activation potentiation (Fowles & Green, 2003). The CMJ was included as a specific dynamic test (Cairns *et al.*, 2005; Thorlund *et al.*, 2009). However, previous research suggests changes to dynamic force generation during the jump may not be reflected in changes to the jump performance itself (Cormack, 2008). Specifically, the ratio of CMJ flight time (Tf) to contraction time (Tc) was shown to change with fatigue, whilst jump was unchanged. This suggested slower rate of force development. Acute NM response during the resistance exercises sets was monitored with repetition sEMG amplitude, MFCV and power measures.

5.1.1 Research Questions

1) What is the difference in acute NM response during, following and 24 hours post-maximum strength and power type resistance exercise sessions?

2) What is the influence of gender on post-session NM response?

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5.2 Methods

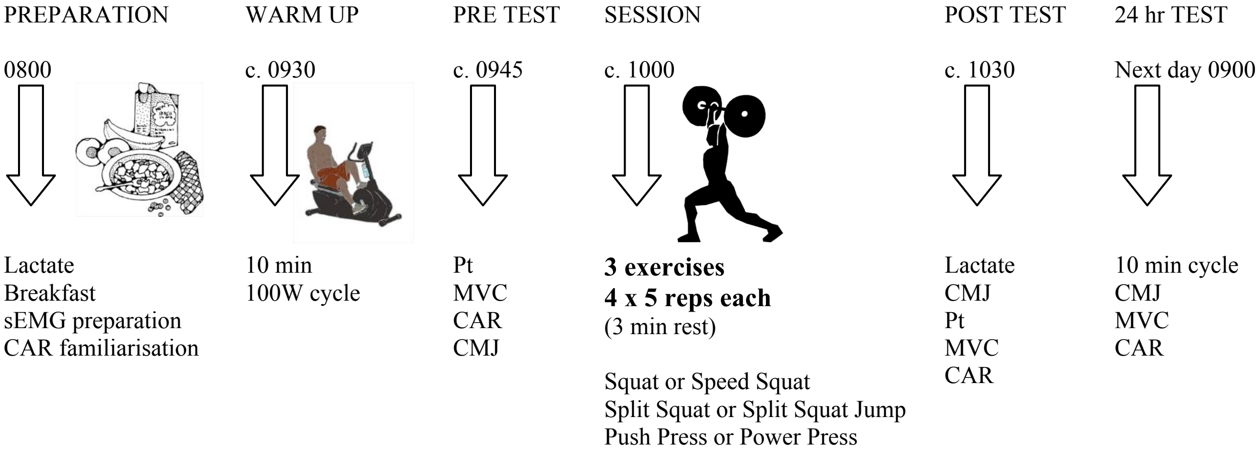

Figure 5.1. Timed summary of the procedures assessing maximum strength & power sessions.

5.2.1 Subjects

Six male and four female subjects were actively recruited from an elite track and field training centre (UK Athletics Olympic Performance Centre, Lee Valley, London). All 10 subjects were national or international standard sprinters or horizontal jumpers, with a minimum of one years experience partaking in regular barbell strength training to enhance competition performance. Table 5.1 shows the physical characteristics of the subjects. Each subject provided written informed consent and the University of Stirling Sports Studies Ethics Committee approved procedures.

Table 5.1 Descriptive data of the subjects' physical characteristics.

	Age (years)	Body mass (kg)	100m best time (s)	Squat 1RM (kg)	Knee extension MVC force (N)
Male, n = 6	28 ± 2	81.2 ± 12.2	10.44 ± 0.37	190 ± 38	1092.5 ± 245.1
Female, n = 4	26 ± 5	60.0 ± 3.7	11.73 ± 0.34	107.5 ± 12	821 ± 102.8

Values are given as mean ± SD.

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5.2.2 Experimental Design

To compare NM fatigue following maximum strength and power training sessions, subjects performed either the maximum strength or power session on two separate days, see figure 5.1. The trials were performed in a random order within seven days, with at least one rest day between each trial. Trials took place post the 2008 summer competition season, therefore all subjects rested between trial days, with no sport-specific training occurring. The female subjects were assessed at the start or middle of their menstrual cycle, to limit the influence of hormonal variation on performance.

Subjects arrived at the testing centre at 0800 hrs in a fasted state and baseline blood lactate measurements were taken with the Lactate Pro device and test strips (ARK Corp, Japan). Consistency of trial times ensured circadian rhythm influence on NM performance was minimised (Racinais *et al.*, 2004; Bird & Tarpenning, 2004). Subjects ate a standardised breakfast comprising cereal with milk or yoghurt and a piece of fruit. Room temperature was recorded at the beginning of each trial to ensure no major differences between days existed, due to possible influence on power and MFCV (Gray *et al.*, 2006; Racinais *et al.*, 2005). Subjects' were familiarised with all the exercises and procedures and the exercise loads were ascertained on a separate visit prior to the trials, see section 5.2.3.

The training session commenced at 0930 hrs with 10 minutes of ergometer cycling (Keiser M3, Keiser Corp, USA) at 100 W as a warm up. Subjects then performed the pre-session NM tests, comprising evoked peak twitch force (Pt), isometric knee extension force assessment (MVC), central activation ratio assessment (CAR) and a vertical jump test (CMJ), see section 5.2.5. The maximum strength or power session was then performed, comprising whole body barbell squat, split squat and press exercises. These are all commonly used by elite strength & conditioning coaches during maximum strength and

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power programmes (*see Appendix 1).* Maximum strength session involved heavy loads, performed with a controlled tempo. The power session involved 30% of the load used in the maximum strength session performed explosively, similar to previous comparative studies (Linnamo *et al.*, 1998).

During both sessions, continuous exercise repetition monitoring was made of sEMG amplitude, MFCV, barbell displacement and knee electrogoniometry measurements. Four minutes following the completion of the final set, blood lactate samples were taken from the earlobe. The suitability of the sample timing was determined in prior pilot testing (*see Appendix 4*). Finally, 10 minutes following the session, CMJ, Pt, MVC and CAR tests were completed, following timings used in previous investigations of NM fatigue post cycle and strength exercise (Bentley *et al.*, 2000; Chiu *et al.*, 2004). 10 minutes was chosen to ensure the fatigue detected was not biased towards the immediate effects of the final set. As strength training is intermittent in structure, NM fatigue may vary immediately post and between sets. Assessment of NM fatigue post exercise needs to assess the overall fatigue resulting from the session. This has a practical significance as athletes often perform strength training followed by other training, such as technical or endurance sessions. On completion of each session subjects provided an overall session RPE rating, using the Borg scale (6-20).

To compare the 24-hour recovery following maximum strength and power sessions, subjects returned to the testing centre the following day at 0900 hours. MVC, CAR and CMJ assessments were performed, following the same cycle warm up procedure.

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5.2.3 Familiarisation and Load Determination Session

Subjects attended the testing centre in separate visit within a seven-day period prior to the trials. Familiarisation with all the NM assessment procedures was completed. This included full instruction and practice of the Pt, MVC, CAR and CMJ assessments. For the CAR assessment, the subjects were familiarised to electrical stimulation with progressively increasing voltage whilst performing sub-maximal isometric knee extension contractions. Then subjects practised performing maximal effort isometric knee extension tests (MVC) and the voltage was superimposed during this contraction. The voltage was progressed up to the highest value subjects were able to tolerate. Recordings were made to confirm this voltage level also resulted in a measurable increase in superimposed force during the MVC (Bilodeau, 2006). This voltage level was subsequently used for the CAR assessment superimposed stimulation during the experimental trials.

In addition, the barbell loads were determined for the maximum strength session exercises of squat, split squat and push press. For each exercise in turn, a series of incrementally loaded sets of five repetitions was performed, starting at a self-selected moderate load. Two to three minutes rest between sets was taken, similar to established recommendations (Baechle, 1994). At the end of each set, subjects rated the intensity of the load against the active muscle rating of perceived exertion (RPE), using the Borg scale (6 to 20). The trial load taken for each exercise corresponded to an active muscle RPE = 16 or 17 (very hard). This enabled the subjects and exercises to be matched for relative intensity. The method was successfully employed in the previous chapter, and the scale has been shown to be a consistent method of assessing strength exercise intensity (Gearhart *et al.*, 2001), giving exercise loads relative to maximum capabilities (Gearhart *et al.*, 2002; Lagally & Amorose, 2007). Whilst repetition maximum loads are normally used in resistance exercise studies, the use of active muscle RPE enables the determination of a load that is repeatable

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across all sets within the session. This is akin to actual methods used by elite athletes: see *Appendix 1* (question 2) for details of how coaches of elite athletes determine and progress load in training. Following recommendations to achieve rating consistency between subjects and trials (Gearhart *et al.*, 2001), subjects were given descriptions of high and low ratings, known as anchors. See *Appendix 7* for a copy of the active muscle RPE Borg scale, with the descriptive anchors.

5.2.4 Maximum Strength and Power Session Procedures

Figure 5.1 summarises the running order and timeline of each trial day. Following baseline measures and breakfast, subjects were prepared with a flexible electrogoniometer attached to the lateral right knee, as described in detail in section 2.2.5. In addition, a sEMG electrode array was attached over the right *vastus lateralis* muscle. For the Pt and CAR assessments, two electrical stimulation pads (4 x 8cm, Campbell Medical, UK) were attached to the proximal, medial thigh aligned over the femoral nerve and over the greater trochanter. These placements followed previous research (Lattier *et al.*, 2004; Nybo & Nielsen, 2001). They were also adopted following pilot testing because they resulted in superimposed force increments above the MVC force without the subject suffering knee pain. This was in contrast to alternative placements upon proximal and distal thigh.

Following the cycle warm up and pre-session NM assessments, two sets of squat were performed at moderate load. This was used as a specific warm up, prior to heavy or fast repetitions required during the sessions. The loads used in the warm up were self-selected by the subjects and reflects typical practice of athletes prior to resistance training. Subjects completed a series of three exercises, four sets of five repetitions each exercise, and three minutes rest between sets. Variation between exercises was used to reflect typical elite training sessions (Aagaard *et al.*, 2002a; Stone *et al.*, 2000). The exercises were performed

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with Olympic lifting barbells (Eleiko, Sweden). During both sessions, following each set, maximum knee angles were checked to ensure subjects retained full and consistent range of motion. Feedback was given to subjects between sets regarding range of movement and controlled timing during the maximum strength session, and range of movement and repetition speed during the power session.

During the maximum strength session, the squat, split squat and push press were performed, in that order, using the pre-determined loads. The squat was performed with the bar resting securely upon the top of the shoulders and the feet shoulder width apart. The exercise involved squatting down until the hips lowered to below knee level on the descent, or eccentric phase, and then standing back up during the concentric phase. The split squat also involved squatting and lifting, with the barbell resting upon the shoulders. However, in comparison to the squat, the right foot was forward and the left foot back. The movement involved squatting down, flexing at the hip and knee of the front leg and the knee of the back leg, whilst keeping the trunk upright. The push press was performed with feet shoulder width apart and holding the barbell in the hands across the front of the shoulders. The movement comprised a small squat down followed by synchronously pressing the bar over the head whilst standing back up. See *Appendix 2* for images of the start and finish positions of each exercise. A metronome, emitting audio pulses at 1 Hz controlled the duration of the exercises. Subjects were instructed to perform the lifting, or concentric phase over two seconds (three beeps), with as constant a tempo as possible.

During the power session the speed squat, split squat jump and power press were performed with 30% of the barbell load used in the maximum strength session, based upon proven power adaptations (Van Cutsem *et al.*, 1998), and similar to previous methods (Linnamo *et al.,* 1998). The movement was the same as the maximum strength session

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exercise equivalent, but performed explosively. During the speed squats, subjects were instructed to perform the eccentric and concentric repetition cycle as fast as possible, with a minimal jump in order to maximise repetition speed. Subjects performed the split squat jumps and power press with maximum acceleration in the concentric phase, following a controlled lowering phase. The techniques used are typical of elite athlete practice.

5.2.5 Neuromuscular monitoring and assessment variables

Section 4.2.5.1 provides a detailed description of the exact sEMG RMS amplitude and MFCV repetition monitoring methods used in this study. Section 4.2.5.2 also provides detailed description of the exact MVC, CAR and CMJ methods used during the pre-, post-, and 24-hour post- session assessments.

RMS amplitude and MFCV values were determined following methods described in section 3.2.3. All barbell exercise repetition and post training session MVC RMS amplitude values were normalised to the reference RMS value captured during pre trial MVC's. Repetition normalised RMS amplitude values during the barbell exercises were processed from the average of the concentric phase of each movement. The MFCV value was processed from a 100 ms time interval centered upon a knee angle of 70° during the concentric phase of these exercises, to limit muscle length changes that may influence MFCV values (Farina & Merletti, 2004; Kossev *et al*., 1992). Normalised RMS amplitude values used to describe levels of activity during exercise sets were defined as the values obtained from repetition one within sets. This is because repetition values changed across sets. Within-set repetition normalised RMS amplitude and MFCV values were processed with respect to repetition one of each set. For simplicity normalised RMS amplitude is referred to as RMS in the following text.

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Pt assessment was performed immediately prior to the combined MVC & CAR assessments. The Pt test used the same knee extension dynamometer (Kin Com, Chattanooga, US) and electrical stimulator (StimISOC, Biopac Systems Inc, USA) and stimulation pads as the CAR test. The stimulator delivered a sub-maximal single triangular pulse of 35 ms duration with a maximum constant voltage of 200 V to the passive quadriceps, similar to previous methods (Fowles & Green, 2003; Morana & Perrey, 2009). The knee was fixed and supported at a flexion angle of 70°, with 0° corresponding to a fully extended knee. Subjects were instructed to relax the leg muscles and not anticipate the electric shock, so the full effect of the stimulation was recorded. The Pt value was taken as the peak change in force from pre-stimulated values, recorded by the dynamometer. During the CMJ test, height was processed directly as the difference between the displacement measured at standing height prior to the jump and displacement at the peak height of the jump, following previous position transducer methods (Cormie *et al.*, 2010b; Nuzzo *et al.*, 2008). The CMJ Tf:Tc ratio was calculated as the flight time (Tf) divided by the contraction time (Tc). This was taken as the period where displacement decreased from the standing height value at the start of the jump to the point when it returned back to this value just prior to take off, whilst the knee joint angle increased and decreased concurrently. The Tf value was taken as the period where displacement increased from, peaked and then decreased back to the standing height value, just after take off, whilst knee joint angle was concurrently unchanged. The mean of the three CMJ height and Tf:Tc values were used for subsequent analysis.

5.2.5.1 Barbell exercise biomechanical measures

Barbell displacement was measured during each repetition in all exercises using a cable-extension linear position transducer device (Celesco PT5A, USA). The free end of the cable was securely attached to the left hand side of the barbell and the device itself was

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placed upon the floor, visually aligned to the subjects left ankle and hip. This set up ensured that the cable ran as vertically as possible during each exercise. The displacement data was used to estimate mean power during the lifting phase of each exercise, following previous methods (Cormie, Deane, *et al.*, 2007; Dugan *et al.*, 2004). The method is described in full in section 2.2.6 and was found to be reliable (Brandon *et al.*, 2011).

For squat, speed squat, split squat and split squat jump repetition mean power this was taken from the whole concentric phase. The start of the concentric phase was where the maximum knee angle (point of maximal flexion) corresponded to the point where displacement started to increase positively. The end of the concentric phase was when the knee returned to 0°, or fully extended. For push press and power press, the mean power calculation was limited to the period where the knee angle was decreasing and displacement was increasing. This was to ensure that the barbell and lifter remained one system, maintaining valid mathematics of the power derivation. Relative repetition mean power, with respect to repetition one of each set, were also processed. This was used to compare changes in power within sets during each session. The time period of the combined lowering and lifting movement were used to define repetition duration of each exercise. This was defined as the difference in time from where knee angle began at 0° (fully extended) and displacement started to decrease and the time point at the end of the concentric phase when the knee returned to 0°. Repetition duration corresponds to the time of the movement. This is simpler to define than time under tension, which implies muscle activity, and may occur without movement during resistance exercise. From the repetition duration and the derived force values, impulse was calculated as the integral of force over time. In addition, total work values were obtained as the integral of power (Winter, 2005). Maximum knee angles, repetition duration, impulse and total work values were obtained using the analysis system's software functions (AcqKnowledge ® 3.8.1, Biopac Systems

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Inc., Santa Barbara, CA). Mean set values from the average of the five repetitions from each set were obtained for concentric mean power, repetition duration, impulse and total work. Total work performed during the entire maximum strength and power sessions was also compared.

5.2.6 Statistical methods and analysis

Descriptive statistics of the within training session variables were processed for RMS amplitude, MFCV, power, impulse, total work and repetition duration and for pre and post session variables for lactate, session RPE, MVC, CAR, Pt, CMJ height, CMJ Tf:Tc, RMS during MVC and MFCV during MVC. For reference, *Appendix 4* shows the reliability statistics of the MVC, CAR and CMJ height variables taken from the combined data from chapters four and five. To compare differences between sessions and times, a two factor general linear model repeated measures ANOVA test (session x time) was processed for MVC, RMS during MVC, MFCV during MVC, CAR, Pt, CMJ height, CMJ Tf:Tc and Lactate. To compare session differences in repetitions within sets and between exercises a three factor ANOVA test (session x set x rep) was processed for RMS amplitude and power and a three factor ANOVA test (session x set x exercise) was processed for power, impulse, repetition duration and total work. Significant main effects were followed by *post-hoc* Tukey's tests. Post-session relative MVC (with respect to pre-session) values were compared for male versus female groups. This was followed with regression analysis to assess the relationship between the post-session relative MVC and squat load. Regression analysis also assessed the relationship between the post-session relative MVC and the system mass load used during the power sessions, expressed in relation to the maximum strength load. Statistical significance was accepted at $p<0.05$. Statistics were performed using Minitab 15 software (USA), which reports statistics to nearest three decimal places.

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5.3 Results

5.3.1 sEMG and mechanical comparison of maximum strength and power sessions

Table 5.2 describes the sEMG and mechanical values during exercise repetitions.

Table 5.2 Normalised RMS, Repetition duration, Impulse, Power and Total Work data during squat, split squat and press during maximum strength and power sessions.

		RMS (%)	Repetition Duration (s) **	Impulse (N.s) **	Mean Power (W) **	Total work (J)
Maximum strength (n = 10)	Squat	70.4 ± 29.6	3.4 ± 0.28	5676 ± 1854	528 ± 245	1791 ± 756*
	Split Squat	60.5 ± 18.8	3.3 ± 0.3	4578 ± 1175	340 ± 130	1089 ± 370
	Press	58.3 ± 24.4	1.9 ± 0.7*	2072 ± 806*	988 ± 389*	1074 ± 334
Power (n = 10)	Speed Squat	74.1 ± 14.7	0.8 ± 0.2	934 ± 228	1234 ± 385*	1004 ± 344
	Split Squat Jump	118.3 ± 29.6*	0.8 ± 0.2	887 ± 206	1760 ± 582*	1119 ± 422
	Power Press	54.6 ± 11.5	0.6 ± 0.2	692 ± 194	3297 ± 1298*	1049 ± 368

Values are given as mean ± SD. Significant session x exercise interaction effects $p<0.01$ were found for all variables with * post hoc significant difference between exercises within sessions shown, $p<0.01$. ** Significant session difference, $p<0.001$ for repetition duration, impulse, and power.

Significant interaction between the exercises and sessions were found for RMS (F = 21.13, $p<0.001$), repetition duration (F = 18.13, $p<0.001$) impulse (F = 97.47, $p<0.001$), total work (F = 8.38, p = 0.004) and mean power (F = 77.37, $p<0.001$). *Post hoc* tests ($p<0.01$) showed impulse and repetition duration were greater and power was less during all three exercises in the maximum strength session compared to the equivalent power session. However, *post hoc* tests between equivalent exercise on maximum strength and power sessions showed only squat exercise had greater total work than the speed squat, and only split squat jump RMS was greater than split squat RMS. The total work performed during

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the maximum strength session of 79.1 ± 26.6 kJ, was significantly greater than the 63.5 ± 20.2 kJ of total work performed during power session (t = 3.65, p = 0.008).

5.3.2 Comparison of Neuromuscular and Lactate response post and 24 hour post maximum strength and power sessions

The absolute values of NM assessments pre, post- and 24-hour post maximum strength and power sessions are shown in table 5.3. Importantly, there were no differences in pre-session values between maximum strength and power session on any variable.

Table 5.3 MVC, RMS during MVC, MFCV during MVC, CAR, Pt, CMJ height and CMJ Tf:Tc, pre and post maximum strength and power sessions. MVC, CAR and CMJ height 24hr post sessions.

		Maximum Strength	Power
MVC (N)	pre	975.5 ± 246.7	983.9 ± 237.8
	post	871.9 ± 255.2*	937.6 ± 298.7
	24 hr	920.5 ± 226.2**	953.3 ± 233.8**
RMS during MVC (%)	pre	100	100
	post	87.5 ± 17.4	94.5 ± 27.0
MFCV during MVC ($m.s^{-1}$)	pre	2.66 ± 0.41	2.88 ± 0.3
	post	2.75 ± 0.51	2.77 ± 0.19
Pt (N)	pre	31.6 ± 17.1	26.7 ± 13.4
	post	26.0 ± 16.3**	22.9 ± 10.9**
CAR (%)	pre	92.6 ± 4.4	94.2 ± 4.9
	post	93.5 ± 3.0	95.4 ± 3.9
	24 hr	92.7 ± 4.7	93.2 ± 4.2
CMJ Height (cm)	pre	49.1 ± 9.8	47.1 ± 10.5
	post	47.8 ± 10.4	47.4 ± 11.1
	24 hr	48.6 ± 8.9	48.7 ± 8.8
CMJ Tf:Tc	pre	0.83 ± 0.19	0.84 ± 0.18
	post	0.78 ± 0.16 $	0.93 ± 0.15 $

Values are given as mean ± SD, n = 10 except for MFCV where n = 7. ** Significant time difference p<0.01 for MVC and Pt, *significant difference p<0.05 pre versus post maximum strength MVC and post maximum strength versus post power MVC, and $ significant session x time interaction for Tf:Tc p<0.001. NB: 24-hour post session measurements were only made for MVC, CAR and CMJ Height.

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MVC was significantly different between sessions (F = 9.37, p = 0.014) and across time (F = 7.83, p = 0.004). In terms of time, *post-hoc* tests revealed MVC was significantly lower post- versus pre- maximum strength session. *Post hoc* tests also showed post- maximum strength MVC was significantly lower in comparison to post- power session (p = 0.02) (see figure 5.2A). Pt was significantly decreased post- in comparison to pre- maximum strength and power sessions (F = 13.05, p = 0.007) (see figure 5.2B). In addition, an interaction effect was found between session and time for Tf:Tc (F = 53.07, p<0.001). P*ost-hoc* tests revealed Tf:Tc was decreased post- maximum strength and increased post- power session (p<0.05) (see figure 5.2C). There were no significant differences or interactions for RMS during MVC, MFCV during MVC, CAR and CMJ height.

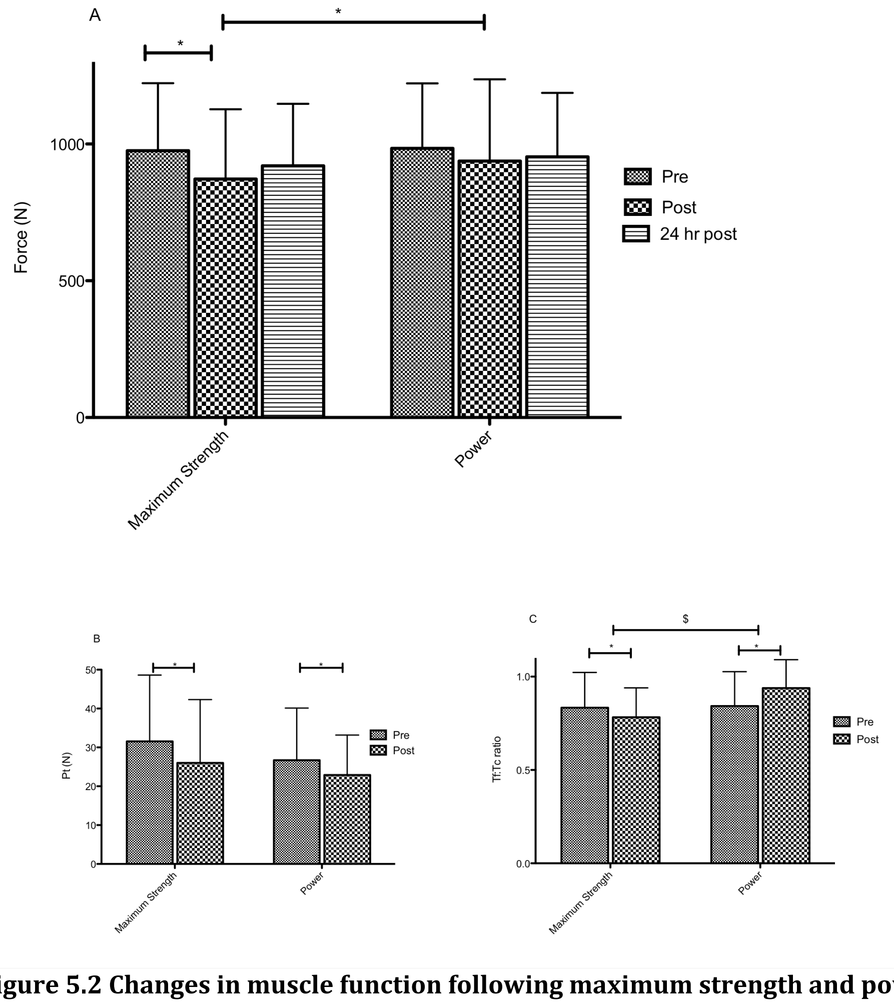

Figure 5.2 Changes in muscle function following maximum strength and power sessions.
Values given as mean ± SD, n = 10. A) MVC pre, post and 24hour post, * significant difference, p<0.05, between pre and post maximum strength and between post maximum strength and power sessions. B) Pt pre and post, * significant difference p<0.01 between pre and post both sessions. C) Tf:Tc pre and post, $ significant interaction, p<0.001 with * significant difference (p<0.05) pre and post for each session.

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There was a significant interaction effect between session and time for lactate (F = 57.56, p<0.001). Figure 5.3 shows that lactate values post- maximum strength session were significantly higher than baseline (6.86 ± 2.2 versus 0.94 ± 0.2 mmol.L^{-1}), whilst power session lactate was unchanged from pre- (0.89 ± 0.2) to post- (1.2 ± 0.3 mmol.L^{-1}). Maximum strength session RPE value (16.5 ± 1.8) was significantly higher than the power session (11.2 ± 2.0) (t = 11.92, p = 0.012).

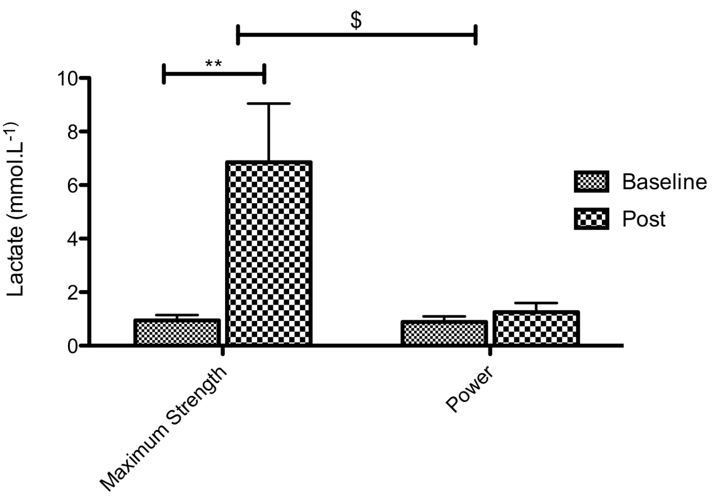

Figure 5.3. Pre- and Post-session Lactate during maximum strength and power sessions.
Values given as mean ± SD, n = 10. ** Significant time difference for lactate and session difference for RPE p<0.01 and $ significant interaction effect, p<0.01.

5.3.3 Comparison of repetition sEMG and power during maximum strength and power sessions

Figure 5.4 shows repetition RMS significantly increased within sets for both sessions (F = 18.76, p<0.001). For example, relative to repetition one of each set, during set four of the maximum strength session, RMS increased to 116.5 ± 14.3%, 125.8 ± 15.6% and 125.8 ± 15.6% for squat, split squat and push press respectively. During set four of the power session RMS increased to 121.1 ± 18.5%, 102.0 ± 13.1%, and 112.7 ± 16.2% for speed squat, split squat jump and power press respectively. There were significant interaction effects found between session and set (F = 4.78, p = 0.029). *Post-hoc* tests revealed repetitions four and five were significantly different to repetition one (p<0.01) during all sets of maximum

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strength session, whereas repetitions four and five were only different during set one of the power session.

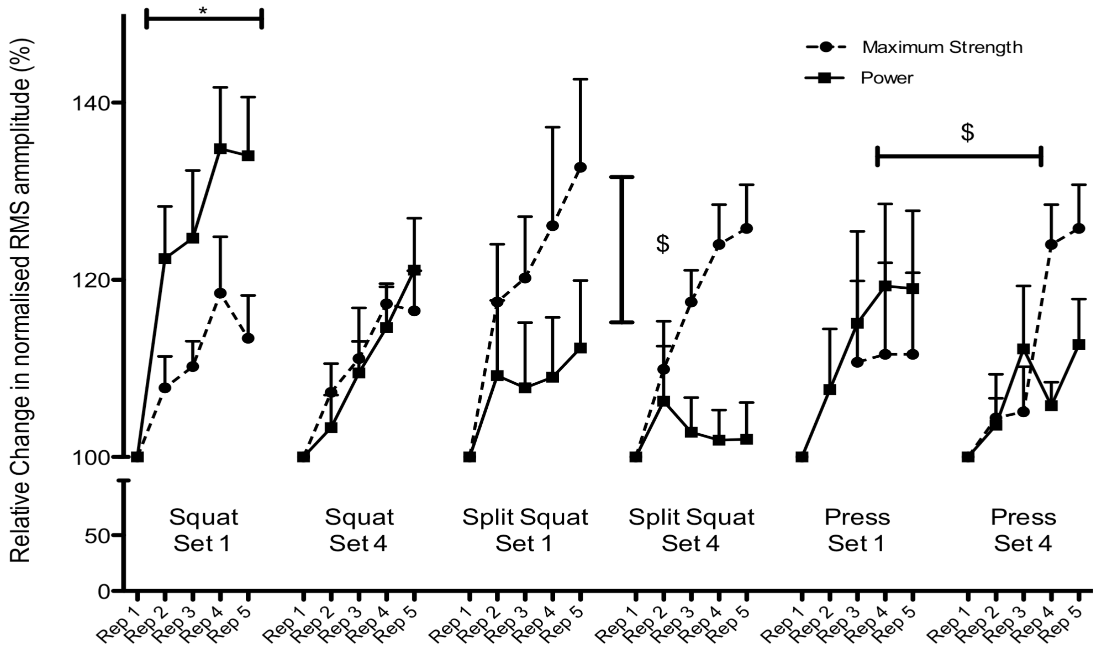

Figure 5.4. Normalised RMS amplitude within sets of maximum strength and power exercises. Mean values given relative to repetition one of each set, n = 10. * Significant difference between repetitions, p<0.001, $ significant interaction effect between set x repetition and exercise x repetition, p<0.05.

NB: *Split squat set 1 and press set 1 were sets 5 & 9 of the sessions respectively.*

Relative to repetition one of each set, MFCV during repetition five was unchanged across repetitions within sets of squat (94.6 ± 11.6%), split squat (99.2 ± 8.8%) and push press (105.3 ± 13.4%) during the maximum strength session, and within sets of speed squat (103.4 ± 15.7%), split squat jump (94.8 ± 6.2%) and power press (100.4 ± 13.9%) during the power session. Repetition mean power, within sets was also unchanged. During the maximum strength session, mean power of repetition five was 102.5 ± 14.1%, 111.2 ± 13.4% and 106.3 ± 21.2% during squat, split squat and push press respectively. During the power session, the mean power of repetition five was 106.4 ± 9.6%, 97.9 ± 14.4%, and 106.9 ± 23.1% during speed squat, split squat jump and power press respectively.

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5.3.4 Changes in relative MVC between gender and strength levels.

The relative change in MVC for male (n = 6) and female (n = 4) subjects, expressed as a percentage of pre-session values, was 89.9 ± 9.3% versus 86.9 ± 5.8% post the maximum strength session and 98.6 ± 5.9% versus 86.4 ± 7.5% post the power session respectively. T-test revealed the female subjects suffered significantly greater decrement in MVC post-power session compared to the males ($t = 2.88$, $p = 0.02$).

There was a significant relationship ($r^2 = 0.705$, $p<0.01$) between the load subjects lifted during the squat exercise and post- power session relative change in MVC, see figure 5.5A. Squat load was used to represent relative strength levels and is expressed as the system mass (bar mass + body mass) divided by body mass. Figure 5.5B shows the significant relationship ($r^2 = 0.744$, $p<0.001$) between post- power session relative change in MVC and the relative load used during the power session in comparison to maximum strength session. This was assessed as relative system mass load between the sessions, as the relative barbell load was fixed at 30% during the power session for all subjects.

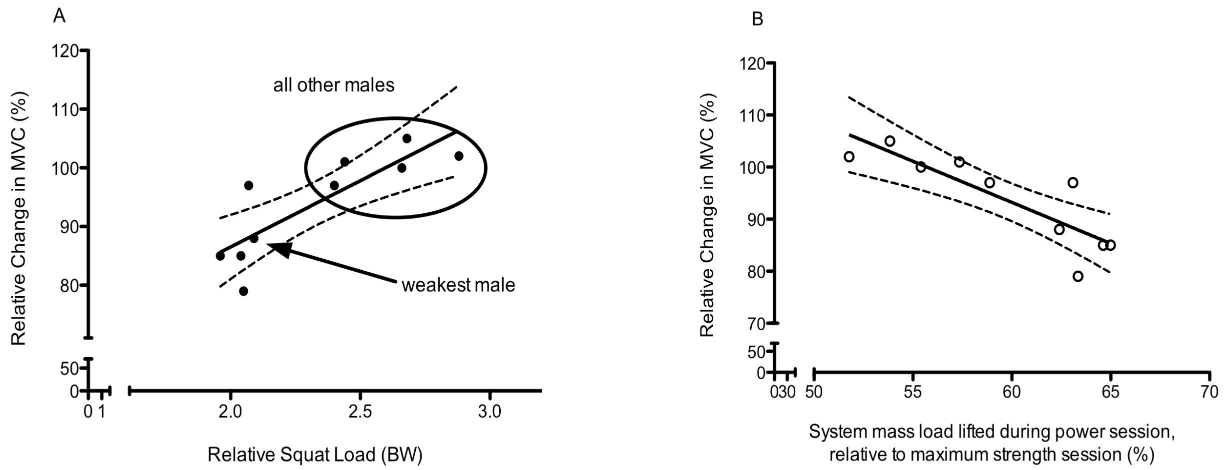

Figure 5.5. Relationships between relative change in MVC post power session and load level.
A) Relative change in MVC versus relative squat load expressed as bodyweights (BW), where post MVC = 0.413 + 0.225 x SM load. ($r^2 = 0.705$, $p<0.01$). Jagged line shows 95% confidence intervals.
B) Relative change in MVC versus load lifting during power session relative to maximum strength session (%), where post MVC = 1.88 - 1.58 x relative load ($r^2 = 0.744$, $p<0.001$). Jagged line shows 95% confidence intervals.

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5.4 Discussion

The important findings were the reduction in MVC and Pt immediately following both sessions, whilst there were no changes in CAR, CMJ height, RMS during MVC and MFCV during MVC. There was significantly greater decrement in MVC following the maximum strength compared to the power session. The findings suggest reduced force generation capacity occurred following both sessions and that force capacity reduced more following maximum strength session. This is most readily explained by the greater total work compared to the power session, associate with greater post- session lactate following the maximum strength session. The difference between maximum strength and power follows previous results of machine exercise sessions (Linnamo *et al.*, 1998). The concurrent reduction in MVC and Pt force assessments with no change in CAR and RMS during MVC, suggests peripheral rather than central fatigue mechanisms were the dominant cause of MVC force decrement (Kent-Braun, 1999). This contradicts previous findings (Hakkinen, 1994), concluding nervous system fatigue had occurred based upon sEMG changes (Linnamo *et al.*, 1998). However, other research using similar methods to the present study found no evidence of central fatigue following three sets of elbow flexion resistance exercise (Tran *et al.,* 2006). Therefore, it seems likely that structured sessions of resistance exercise, designed for maximum strength and power adaptation, result in primarily peripheral fatigue.

It is perhaps surprising that the resistance exercise sessions did not result in central fatigue as the central pathways of the NM system are involved in maximum strength and power exercise adaptation (Aagaard *et al.*, 2002a; Aagaard *et al.*, 2000; Sale, 1988). This suggests that chronic neural adaptation and acute central fatigue are unrelated. During the maximum strength and power sessions, repetition RMS increased within the sets, with no changes in repetition mean power, following findings from chapter four. This indicates greater recruitment and/or firing rates, possibly of the larger fast twitch motor units. Therefore, perhaps the stimulus for adaptation is not the degree of central fatigue following the session, but instead the degree of muscle activation required to maintain repetition power during sets of dynamic resistance exercise (Takarada, Takazawa, *et al.*, 2000).

A further difference between the sessions was the greater increase in repetition RMS within sets of maximum strength in comparison to power session. This suggests greater NM activation was required to maintain repetition performance of heavy load, compared to low load high velocity repetitions (Moritani *et al.*, 1986; Sogaard *et al.*, 2006). The peripheral fatigue indicated by decreased MVC and Pt, was probably due to the repeated eccentric and concentric contractions, resulting in local muscle damage (Jones, 1996) and/or accumulation of metabolites affecting the release and re-uptake of Ca^{2+} in the sarcoplasmic reticulum (Hill *et al.*, 2001). It is possible that the greater peripheral fatigue following maximum strength type training provides a greater stimulus for muscle protein synthesis (McDonagh & Davies, 1984; Schoenfeld, 2010).

Additionally, a difference between the sessions was found for CMJ Tf:Tc ratio, despite no change in CMJ height. Tf:Tc increased post- power session and reduced post- maximum strength. Unaltered jump performance despite decreased force capacity may be explained by muscle power compensation due to muscle temperature increases (Asmussen, Bonde-Petersen, & Jorgensen, 1976; Stewart *et al.*, 2003). Greater Tf:Tc implies the same jump performance resulted from less contraction time, suggesting RFD was increased in the eccentric phase of the jump (Cormie *et al.*, 2009). This may be due to increased inter-muscular co-ordination or leg spring stiffness following the high velocity power exercises (Comyns *et al.*, 2007; Comyns *et al.*, 2006; Gullich & Schmidtbleicher, 1996).

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Contrary to the previous chapter, there were no significant changes found in repetition MFCV. This was likely due to methodological issues, as processing MFCV was only possible for seven subjects. Similar to the previous studies, there were difficulties in MFCV preparation and obtaining signal correlation, see sections 3.4 and 4.4. In fact MFCV did reduced during the maximum strength session squat, but the difference was not quite significant ($p = 0.06$).

The 24-hour recovery in NM function following both sessions was also assessed. MVC, CAR and CMJ were not different 24-hours post either session. However, MVC was 6% below pre-session values 24-hours following the maximum strength session. Although this was not a significant change it suggests recovery of force generation capacity was not complete for some subjects, which is a consideration for training planning.

In general, the previous studies of strength and power sessions showed greater acute MVC decreases and incomplete recovery 24-hours post trials (Hakkinen, 1993; Hakkinen, 1994; Linnamo *et al.,* 1998). These differences are likely due use of repetition maximum loads and the higher repetition number used in the previous studies, compared to the more realistic loads and session structure in the present study. Elite athletes rarely perform sets of resistance exercise where each set is performed to maximum and the loads reduce as the session progresses, except during sessions specifically targeting the development of muscle hypertrophy (Ahtiainen *et al.*, 2003). Therefore the degree of fatigue and the rate of recovery shown in this study is perhaps more representative of elite maximum strength and power type sessions. The change in MVC following 12 sets of barbell maximum strength exercise was greater than that found following five sets in the previous chapter, at a similar intensity, which is to be expected.

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Another methodological difference between this and previous studies is the timing of post-session NM assessments. These were made 10-minutes following the completion of the final set, rather then immediately following the final repetition of the final set. The immediate effects of the repetitions, such as ischemia or muscle pH changes, may influence action potential propagation and contractile function, which influence both MVC and RMS measures (Fitts, 1994). This may bias the findings towards the acute response to the preceding set, and not the impact of the entire session. Therefore, 10 minutes was selected to ensure that the NM fatigue to the whole session was assessed, following previous timings (Chui *et al.*, 2004). However, the previous studies found that the immediate decreases in MVC were maintained one-hour post-session. Therefore, perhaps the post-session timing is not especially critical for the MVC force test. This is may be related to prolonged effects of peripheral fatigue mechanisms following exercise (Sogaard *et al.*, 2006). The choice of assessment timing was more likely to have influenced the CAR measurement, as central fatigue has been shown to recover quickly (Behm & St-Pierre, 1997; Sogaard *et al.*, 2006; Taylor *et al.*, 1996). Therefore, the present findings should be interpreted as limited evidence of central fatigue, 10 minutes post- maximum strength and power sessions.

The secondary aim of the study was to compare NM response between male and female subjects. The relative post-session change in MVC was used to assess this. However, care should be taken in the interpretation of the results due to the low subject numbers. Both male and female subjects showed reduced MVC post- maximum strength session. However, only female subjects showed significantly reduced MVC post- power session. In fact, female subjects suffered a 12% reduction in MVC following both sessions, whereas male subjects had reduced MVC force by 11% and 1% following maximum strength and power sessions respectively. This is contrary to previous findings, which showed similar reductions in MVC of c. 11% in men and women post power type sessions (Linnamo *et al.*, 1998). Previous research has shown that when females are matched for strength, there is no difference in fatigue to men (S. K. Hunter, Critchlow, Shin, & Enoka, 2004). However, strength levels were not matched in this study (see table 5.1). This suggests that individual strength levels may also account for the difference in NM fatigue. Further analysis was performed using squat load relative to body mass to represent strength levels. A relationship was found between strength and the relative change in MVC following the power session (figure 5.5A), but not post- maximum strength session. This led to the insight that there was variation in the relative loading level used between subjects during the power session. This was because power session exercise load was set at 30% of maximum strength barbell load. This was based upon established methods for power type resistance exercise (Cormie *et al.*, 2010b; Van Cutsem *et al.*, 1998). However, because free-weight Olympic style exercise involves lifting both ones own body mass and the additional barbell mass, the actual load lifted should be considered in system mass terms (body mass + bar mass). In fact, the system mass load lifted during the power session was not 30% of the maximum strength load, but varied between 50 and 65%. Subsequent analysis showed that the system mass load lifted during the power session (relative to the loaded lifted during the maximum strength session) was inversely related to the degree of change in MVC post power session (figure 5.5B). Consequently, the most likely explanation for the difference in MVC force reduction between male and female subjects is that the weaker, lighter subjects were working relatively harder during the power session.

The present study does not provide definitive evidence of the influence of gender on acute NM fatigue following maximum strength and power resistance exercise sessions. Nonetheless, the insight that free-weight exercise loads should be considered in system mass terms is a useful practical outcome. Based upon the previous machine exercise

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power session findings, coaches may have assumed that little fatigue occurs. In contrast, this study has shown this is not necessarily the case when barbell power exercises are used, depending upon strength levels and body mass. Setting load levels for power sessions as percentages of system mass loads may help ensure individuals train at similar intensity. Further study comparing resistance exercise sessions using a range of relative system mass load may confirm this.

5.5 Summary and Conclusion

To the researcher's knowledge, this is the first study to investigate maximum strength and power sessions using a comprehensive NM test battery that includes Pt and CAR measures. This had provided detailed information in comparison to previous studies, and enabled the NM response to be related to peripheral fatigue for male and female subjects. The study was also designed specifically to represent elite training methods, assessing elite athletes, barbell exercises, and a typical session volume and structure (Aagaard *et al.*, 2000; Cormie *et al.,* 2010b). The findings show that 12 sets of maximum strength and power resistance exercise results in force generation capacity decrement that may take up to 24-hours to recover. Coaches may now plan training programmes knowing the degree and time course of recovery. For example, training with no more than 12 sets may avoid incomplete recovery the following day. The degree of fatigue and recovery is more pronounced following maximum strength type training, as a result of the greater total work of the session. The findings suggest acute nervous system fatigue is not necessary for the NM adaptations associated with maximum strength and power training. Instead, muscle activation during exercise repetitions may be the critical NM stimulus. However, the causative link between the acute NM response and chronic adaption is beyond the scope of this study and requires further investigation. Differences were shown in the degree of

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fatigue following the power session between male and female subjects. However, analysis showed that the relative load used during the power session differed between individuals.

Limitations to this study may include the variation between exercises and lack of sufficient subjects of either gender, which assumes both male and female elite athletes responded similarly. In addition, the use of a metronome is contrary to normal practice during heavy barbell lifting and may change the NM recruitment strategies of the lifter. Therefore, the following study aims to investigate high intensity strength and power training with no restrictions in movement speed, to further explore the acute NM response to elite strength and power training. The following study is also designed to achieve greater experimental control, using a larger sized elite subject group, antagonist muscle measures and relative system mass loads during power type sessions.

Chapter Six

Acute neuromuscular and hormonal response to high intensity heavy, moderate and light load barbell squat resistance exercise sessions in elite power athletes

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6. *Acute neuromuscular and hormonal response to high intensity heavy, moderate and light load barbell squat resistance exercise sessions in elite power athletes*

6.1 Introduction

Elite athletes perform specific types of resistance exercise to develop different physical adaptations. Training for muscle hypertrophy involves high volume sessions at 50 - 80% RM (Fry, 2004; Holm *et al.*, 2008), whilst maximum strength development training involves low volume at 80 – 95% RM intensity (Aagaard *et al.*, 2002a; Campos *et al.*, 2002). In addition, training for improved power comprises low volume sessions at 30% RM performed at high velocity (Cormie *et al.*, 2010b). The acute hormonal and neuromuscular (NM) responses to training sessions are significant in relation to chronic training adaptations (Kraemer *et al.*, 1990; McCall *et al.*, 1999; Hakkinen 1994: McCauley, *et al.*, 2010). For example, increased Testosterone (T) post high volume resistance exercise has been linked to increased muscle protein synthesis (Ahtiainen *et al.*, 2003), due to enhanced cell receptor interactions (Ronnestad *et al.*, 2011). Reduced force generation capacity (MVC) related to peripheral fatigue mechanisms may indicate the stimulus needed to promote muscle protein synthesis (McDonagh & Davies, 1984; Schoenfeld, 2010). Finally, NM fatigue related to central activation, or reduced neural drive, may indicate the stimulus for enhanced muscle activation associated with maximum strength development (Hakkinen, 1994). However, the previous chapter found no evidence of central fatigue following maximum strength and power type sessions, similar to findings following dynamic exercise (Behm *et al.*, 2002; Klass *et al.*, 2004; Tran *et al.*, 2006). Instead, as chapter four demonstrated, increased electromyographic (sEMG) amplitude during repetitions of resistance exercise may indicate greater acute motor unit recruitment, thereby providing the NM stimulus required for chronic adaptation (Ahtiainen & Hakkinen, 2009; Gonzalez-Izal *et al.*, 2010; Pincivero *et al.*, 2006).

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The hormonal and NM responses to hypertrophy and high volume maximum strength type sessions, as defined above, have been studied extensively (Ahtiainen *et al.*, 2004; Hakkinen & Pakarinen, 1993). However, elite athletes commonly perform resistance exercise sessions using a variety of speeds and load intensities (Schmidtbleicher, 1992). Related to power type training, explosive lifting is performed to optimise rate of force generation capabilities (R. U. Newton *et al.*, 1997). McCauley *et al.* (2010) compared the hormonal and NM responses to maximum strength, hypertrophy and power type sessions, matched for total work. Interestingly, sEMG activity during MVC reduced following maximum strength and not hypertrophy, suggesting central fatigue was specific to the session type. In addition, MVC and rate of force development (RFD) were reduced following hypertrophy and maximum strength, but not power session. In contrast, Chui *et al.* (2004) showed significant fatigue (reduced RFD and MVC) following a power-type session of moderate load performed explosively, which they termed high-intensity resistance exercise. Initial RFD reduced more than MVC, which the researchers related to peripheral fatigue mechanisms. These studies suggest changes in RFD may vary with session type, and also in comparison to MVC. RFD is affected by alterations in neural drive, due to the influence of fast motor unit activation on force generation (Aagaard *et al.*, 2002a; Van Cutsem *et al.*, 1998), and so may further indicate NM adaptation processes. Importantly, the previous conclusions of the nature of NM fatigue were based on indirect or limited evidence. Central fatigue cannot be assumed from sEMG measurements alone (Sogaard *et al.*, 2006). However, specific measures such as Central Activation Ratio (CAR) and evoked peak twitch force (Pt) provide more direct information regarding central (e.g. motor neuron firing) and peripheral (e.g. excitation-contraction coupling) NM fatigue mechanisms (Kent-Braun, 1999). In addition, the previous chapters have demonstrated that monitoring of sEMG during resistance exercise provides critical information of the NM response, which may also inform the adaptation stimulus.

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To the researcher's knowledge, no studies have compared the NM response to high intensity resistance exercise performed with varied load. This is of interest as elite athletes perform explosive barbell exercises across a range of loads. Furthermore, improvements in both power and maximum strength have been found following explosive lifting at heavy or light loads (Moss *et al.*, 1997). This suggests exercise execution has a significant influence on adaptation, possibly more than load. This is because the maximal effort required in order to lift a load as fast as possible, results in enhanced NM activation that is critical to both power and maximum strength adaptation (Behm, 1995; Behm & Sale, 1993a). Even if high loads prevent fast execution, the voluntary effort optimises the neural drive to the muscles (Ives & Shelley, 2003). Therefore, explosive lifting execution may influence NM response, and warrants further analysis. A specific comparison of hormonal and NM responses to explosive lifting across a range of loads does not exist, and may further understanding of the load that optimises NM adaptation. Therefore, the primary aim of this study is to establish the hormonal and NM response to high intensity resistance exercise at three load levels. Specifically, how RFD and MVC change, along with other NM measures to assess the nature of fatigue. It is expected that, high intensity heavy load training will induce central fatigue and the greatest post-session hormone response.

The hormonal responses to resistance exercise are well documented. However, few studies discuss the influence of the acute response of the hormones on NM recruitment (Bosco *et al.,* 2000). Testosterone (T) levels have been linked to dynamic NM performance (Cardinale & Stone, 2006), and so the acute hormonal response may influence pre- and post-session assessments. Therefore, monitoring the T response may help explain changes in post-session NM function. Consequently, a secondary aim of this study is to investigate if any relationships exist between post-session T and NM performance.

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The findings from chapter five showed that relative load levels during lighter power sessions vary between individuals when barbell exercise is performed. This is because power session loads are typically determined as a percentage of maximum strength session loads. However, relative loads of barbell exercises must be based upon the whole system mass (bar + body mass). The present study uses relative system mass loads to ensure parity between subjects during the moderate and light sessions. Therefore, it is expected that individual strength levels will not influence post-session NM response during the power type sessions, unlike the previous chapter. The influence of strength level on changes in post-session NM response will be assessed to confirm this outcome.

6.1.1 Research Questions

1) What is the different in NM response during and following high intensity barbell squat resistance exercise sessions at three distinct load levels? Specifically, what degree of change in RFD, MVC and other NM assessments occurs mid- and post- each session?

2) What are the relationships between the post-session T and NM responses?

Hypotheses:

1) The heavy session results in the greatest T and NM fatigue response.

2) Strength level does not influence post- moderate and light session NM response due to the use of system mass loads.

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6.2 Methods

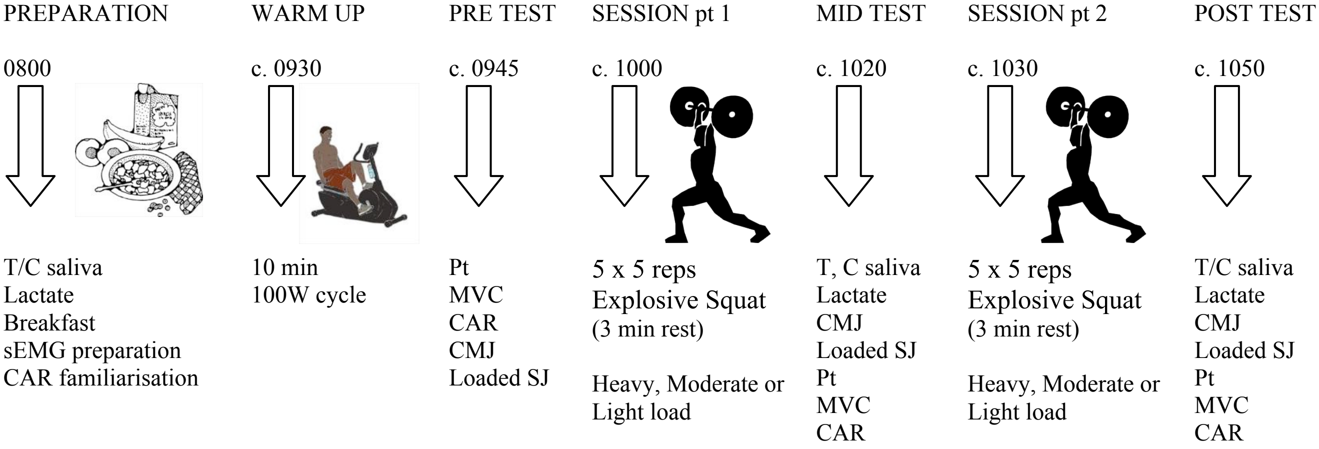

Figure 6.1. Timed summary of the maximum strength v explosive v speed squat procedures.

6.2.1 Subjects

Eleven male and four female subjects were actively recruited from elite track and field and elite rugby. All possessed a minimum of three years experience in regular barbell strength training to enhance their sport performance. Table 6.1 shows the physical characteristics of the subjects. Previous data suggests limited difference in NM fatigue between gender following strength and power sessions (Linnamo, *et al.*, 1998). However, the range of strength levels within the subject group enabled the use of relative system mass loads during the moderate and light sessions to be assessed. Each subject provided written informed consent and the University of Stirling Sports Studies Ethics Committee approved procedures.

Table 6.1 Descriptive data of the subjects' physical characteristics.

	Age (years)	Body mass (kg)	CMJ (cm)	Squat 1RM (kg)	MVC knee extension (N)
Male, n = 11	26 ± 3	86.0 ± 12.5	51.2 ± 4.9	152.1 ± 25.8	1174.5 ± 200.4
Female, n = 4	26 ± 3	66.0 ± 5.2	39.1 ± 4.4	96.6 ± 9.1	836.5 ± 61.7

Values are given as mean ± SD.

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6.2.2 Experimental Design

To compare the hormonal and NM response to heavy, moderate and light load high intensity barbell squat resistance exercise sessions, three separate trials were performed. Subjects performed the moderate, then heavy and then light sessions with at least one days rest between trial days, over a maximum of 14 days. Trials took place post the 2009 Athletics summer competition season, therefore all subjects rested between trials, with no sport-specific training occurring. The female subjects were assessed at the start or middle of their menstrual cycle, to limit the influence of hormonal variation on performance. Subjects arrived at the testing centre at 0800 hrs in a fasted state. Baseline blood lactate measurements were taken with the Lactate Pro device and test strips (ARK Corp, Japan) and saliva samples for hormone analysis were collected (see 6.2.4.2). Consistency of timings and environmental controls followed methods detailed in sections 4.2.2 and 5.2.2. Subjects' were familiarised with all the exercises and procedures, also following previous methods detailed in 5.2.3. The training session commenced at 0930 hrs with 10 minutes of ergometer cycling (Keiser M3, Keiser Corp, USA) at 100 W as a warm up. Subjects then performed the pre-session NM tests, comprising evoked peak twitch force (Pt), isometric knee extension force assessment (MVC and RFD), central activation ratio assessment (CAR), a vertical jump test (CMJ), and a loaded Squat Jump (SJ) test. Loaded SJ power assessment was included as a specific load and velocity test (Cairns *et al.*, 2005). Surface electromyography (sEMG) amplitude was assessed during the MVC and RFD assessments. The latter was use to specifically represent initial onset motor unit activation, which has been shown to be critical to RFD performance (Van Cutsem *et al.*, 1998). Rate of twitch development (dF/dt) was processed in addition to Pt, as it may represent post-activation potentiation independent of fatigue (Edwards *et al.*, 1977; Fowles & Green, 2003). Post activation potentiation was related to high intensity squat post-session NM response (Chui *et al.,* 2004), but was not directly assessed.

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The heavy, moderate, or light load high intensity session was then performed. The session comprised two series of five sets x five repetitions of barbell squat exercise, performed explosively. Three minutes rest was taken after each set. NM assessments were made again following the fifth (mid-session) and 10^{th} set (post-session). The mid session assessments occurred between five and ten minutes following the completion of the fifth set. Post-session tests occurred ten minutes following the completion of the final set. Mid-session assessments were used to detect any possible variation in the rate of change between RFD and MVC assessments across the sessions. Blood lactate samples were taken from the earlobe and saliva samples collected immediately following the fifth set (mid-session) and four minutes following the final set (post-session). During all three sessions, continuous exercise repetition monitoring was made of sEMG amplitude, barbell displacement and knee electrogoniometry measurements. On completion of each session subjects provided an overall session RPE rating, using the Borg scale (6-20).

6.2.3 Heavy, Moderate and Light High Intensity Session Procedures

Figure 5.1 summarises the running order and timeline of each trial day. Following baseline measures and breakfast, subjects were prepared with a flexible electrogoniometer attached to the lateral right knee as described in detail in section 2.2.5. For sEMG measurements a pair of adhesive gel 10mm diameter electrodes (Campbell Medical Supplies, UK), with 10mm inter-electrode distance, was placed upon the right *vastus lateralis* muscle. The area of skin covering the approximate recording site was first shaved, abraded and cleaned. The electrodes were placed at two thirds down the line visualised from the greater trocanter to the lateral side of the patella, following SENIAM guidelines (Hermens *et al.*, 1999). For the Pt and CAR assessments, two electrical stimulation pads (4 x 8cm, Campbell Medical, UK) were attached to the proximal, medial thigh aligned over the femoral nerve and over the greater trochanter (Lattier *et al.*, 2004; Nybo & Nielsen, 2001). They were also

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adopted following pilot testing because they resulted in superimposed force increments above the MVC force without the subject suffering knee pain. This was in contrast to alternative placements upon proximal and distal thigh. Following the cycle warm up and pre-training session NM assessments, two sets of squat were performed at moderate load. This was used as a specific warm up, using self-selected loads. This reflects typical practice of athletes prior to high intensity resistance exercise.

During the heavy session subjects lifted a load corresponding to their subjective active muscle RPE = 16 – 17 (very hard), as per chapters four and five. The heavy session loads were previously established during the familiarisation session. During which, subjects performed a series of sets of five repetitions, of incrementally loaded explosive barbell squat. Two to three minutes rest between sets was taken, similar to established recommendations (Baechle, 1994). At the end of each set, subjects rated the intensity of the load against the active muscle rating of perceived exertion (RPE), using the Borg scale (6 to 20). Load was increased until a rating of 16 - 17 was obtained. During the moderate and light sessions, subjects lifted 75% and 50% of heavy session load respectively, in system mass terms. System mass is the total barbell and body mass combined. The loads were comparable to previous studies of maximum strength and power type sessions (Cormie *et al.*, 2010a, 2010b; McCaulley *et al.*, 2009).

During each trial, the squat was performed with the bar resting securely upon the top of the shoulders and the feet shoulder width apart. The exercise involved squatting down until the hips lowered to knee level on the descent, and then subjects re-extended the knee and hip as explosively as possible to return to the standing position. During heavy and moderate sessions subjects squatted down at a controlled speed in time to a metronome, emitting audio pulses at 1 Hz. During the light session subjects performed the eccentric

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and concentric repetition cycle as fast a possible. However, subjects were instructed not to jump, so that repetition speed was optimised. The techniques used are typical of elite athlete practice. Verbal encouragement and feedback was given during and following each set. The data from the software screen (AcqKnowledge ® 3.8.1, Biopac Systems Inc., Santa Barbara, CA) was checked to ensure subjects executed repetitions maximally and maintained range of motion throughout the sessions.

6.2.4 NM monitoring, assessment and hormone analysis procedures

Previous methods described in 3.2.3 detail the how sEMG root mean square (RMS) amplitude was obtained and processed from the *vastus lateralis* muscle. The MFCV measurement was discontinued due to subject preparation difficulty and the inability to glean a full data set in previous chapters. Consequently, as stated above, bi-polar adhesive electrodes were used and not an electrode array as in chapter 3. All RMS amplitude values during barbell squat repetitions and MVC and RFD tests were normalised to a reference RMS amplitude value captured during pre trial MVC assessment. Repetition normalised RMS amplitude values during the squat repetitions were processed from the average of the concentric phase of each movement. Normalised RMS amplitude values used to describe levels of activity during exercise sets were defined as the values obtained from repetition one within sets. This is because repetition values changed across sets. Within-set repetition normalised RMS amplitude values were processed with respect to repetition one of each set. For simplicity normalised RMS amplitude is referred to as RMS in the following text.

As an additional control variable, RMS was also measured during the knee extension MVC and squat exercise from the *biceps femoris* (BF) muscle, following procedures for *vastus lateralis* (VL) and using recommended BF electrode placements (Hermens *et al.*, 1999).

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These were made to assess the influence of antagonist muscle activity under fatigue (De Luca, 1997; Hassani *et al.*, 2006; Weir *et al.*, 1998; Zory *et al.*, 2010). To enable comparison between trial days and subjects, the BF RMS amplitude was normalised relative to the maximum RMS amplitude obtained during a knee flexion MVC assessment. This was performed prior to the sessions, at a knee angle of 30° (in relation to full extension of 0°) whilst subjects were securely seated at a hip angle of 90° in the dynamometer (Kin Com, Chattanooga, US). Subjects were required to perform maximal voluntary isometric knee flexion for up to 5 seconds until maximum force had been achieved and maintained. The knee flexion MVC force value and maximum BF RMS value were processed from the 200 ms epoch corresponding to the peak force value.

Section 4.2.5.2 provides detailed description of the MVC, CAR and CMJ methods used during the pre-, mid and post-session assessments. The instructions given to subjects during the MVC assessment were modified from the previous chapters. In this study subjects were verbally encouraged to engage maximum force as quickly as possible (Aagaard *et al.*, 2002a). This enabled a valid RFD value could be obtained from the same assessment. The raw force-time data, sampled at 2000 Hz, was exported into a bespoke Excel worksheet and RFD was taken as the average slope of the force-time curve during the first 50 ms, 100 ms and 200 ms post the onset of force application. The onset of rate of force development was defined as the time point where force increased above 5% of the MVC force value and continuously rose subsequent to this point. This method avoided either signal noise or small movements of the leg leading to fluctuations in force values that would false trigger the onset of RFD measurement. All three RFD values were correlated with each other ($r > 0.80$), and so for brevity average RFD from the initial 100ms was used in the analysis to represent RFD. The mean RMS was also processed from the same 100 ms epoch, giving the RMS during RFD test value.

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Pt assessment followed methods described in 5.2.5. In addition, dF/dt was processed from the same evoked twitch. The value was obtained by dividing the change in force between the resting and peak values by the time between the onset of the twitch and the peak force. Therefore an average dF/dt for the Pt was processed using the software functions (AcqKnowledge ® 3.8.1, Biopac Systems Inc., Santa Barbara).

The loaded squat jump (SJ) assessment was performed following the CMJ test. The loaded SJ was performed using the barbell load from the explosive session (75% of maximum strength session load in system mass terms). The barbell was placed upon the shoulders, as per normal for the squat exercise. Subjects lowered down until in a half squat position, and then paused at approximately 90° knee angle. After a count of 2 s, upon the researcher's command, the subjects jumped upwards as explosively as possible, keeping the barbell upon their shoulders. Loaded SJ displacement was measured using the cable extension linear position transducer (Celesco, PT5A) attached to the barbell, in the same way as displacement was determined from CMJ assessment, see 4.2.5.2. Subsequently, peak power was processed from this displacement data following processing methods described in chapter two. The peak power variable was obtained from the concentric phase of the movement only, similar to previous loaded squat jump assessments (Cormie *et al*., 2008; Hori *et al*., 2006).

Mean power, impulse, repetition duration and total work were obtained and processed for each squat repetition during sets of each session, following methods described in 5.2.5.1.

6.2.4.1 Hormone sampling and analysis

Saliva samples were taken three times prior to breakfast, mid- and post- each session. The saliva was collected into sealable collection tubes. Subjects were seated during this sample

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collection. The samples were stored in a laboratory freezer (-80°C) until assay. Subjects were instructed and familiarised with the saliva sample collection method prior to the trial days and baseline hormones were taken over a comparable time period on this familiarisation day from nine subjects. Assays were analysed for testosterone (T) and cortisol (C) concentrations using enzyme-linked immunosorbent assay kits (Salimetrics Europe, Newmarket, UK) using a MRX Microplate reader (Dynex Technologies, UK). The minimum sensitivity for T was 1 $\mu g.mL^{-1}$ and for C was 0.003 $\mu g.mL^{-1}$. Regression analysis showed no inter-plate differences, with identical slopes and intercepts.

6.2.5 Statistical methods and analysis

All data was expressed as mean ± SD. To compare differences between sessions and time a two factor general linear model repeated measures ANOVA test (session x time) was processed for MVC, RFD, RFD:MVC ratio, VL and BF RMS during MVC, VL RMS during RFD, CAR, Pt, dF/dt, CMJ height, CMJ Tf:Tc, Loaded SJ peak power, lactate, T, C and T:C ratio. To compare session characteristics two factor ANOVA test (session x set) was processed for power, impulse, repetition duration and total work. To compare session differences in repetitions within sets and between exercises a three factor ANOVA test (session x set x rep) was processed for RMS amplitude and power and a three factor ANOVA test (session x set x exercise) was processed for power, impulse, repetition duration and total work. Significant main effects were followed by *post-hoc* Tukey's tests. Due to methodological issues, not all measurements for evoked twitch and CAR assessments were recorded. In addition some subjects were unable to produce saliva samples within the time frame to maintain consistency of the NM assessments. Therefore, two factor ANOVA was performed with nine subjects for Pt, dF/dt and CAR and 11 subjects for T, C and T:C variables.

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To assess the relationships between strength levels and session responses and also to investigate any relationships between relative post session NM and hormone responses, a Pearson's correlation analysis was performed between MVC, RFD, CMJ height, T and T:C, and strength level. Linear regression plots were made between variables with significant relationships. Strength level was expressed as relative squat load to body mass ratio and also as MVC force values normalised to body-mass to the power of 0.67, following previous recommendations (Jaric, Mirkov, & Markovic, 2005). This methodology ensures subject's strength levels over a range of body mass values are fairly established. This method means body scaling issues do not influence strength level; where mass is related to the three-dimensional volume, whilst strength which is related to two-dimensional cross sectional area. Statistical significance was accepted at $p<0.05$. Statistics were performed using Minitab 15 software (USA), which reports statistics to nearest three decimal places.

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6.3 Results

6.3.1 Mechanical and sEMG description of heavy, moderate and light high intensity squat sessions

Table 6.2 summarises the mechanical characteristics of high intensity squat exercises at heavy, moderate and light load sessions. Significant differences were found between sessions for power (F = 232.65, p<0.001), repetition duration (F = 295.40, p<0.001) and impulse (F = 124.58, p<0.001). A significant interaction was found for session by set for power (F = 8.82, p = 0.001). *Post hoc* tests revealed mean set power was significantly lower during set five (p<0.05), and set 10 (p<0.001) compared to set one of the heavy session, but was maintained across sets during moderate and light sessions. The total work performed during the whole of each session was not different at 92.5 ± 27.3, 73.9 ± 25.7, & 74.4 ± 19.9 kJ for the heavy, moderate and light sessions respectively. There were no within or between sessions differences in mean set RMS values for both VL and BF muscles during sets one, five and ten of each session, see figure 6.2.

Table 6.2. Power, impulse and repetition duration for set 1, 5 & 10 and total work for all sets during heavy, moderate and light sessions

		Heavy	Moderate	Light
Power (W)**	Set 1	1157.0 ± 383.7	1708.0 ± 522.1	2170.0 ± 489.0
	Set 5	978.1 ± 305.2*	1786.0 ± 576.7	2281.0 ± 538.7
	Set 10	881.1 ± 259.9*	1778.0 ± 523.2	2272.0 ± 578.1
Impulse (N.s)**	Set 1	4559.0 ± 1178.0	3144.0 ± 750.1	925.8 ± 224.6
	Set 5	4802.0 ± 1177.0	2964.0 ± 604.3	943.3 ± 244.2
	Set 10	4855.0 ± 1296.0*	3028.0 ± 619.9	945.1 ± 235.9
Repetition duration (s)**	Set 1	2.5 ± 0.3	2.1 ± 0.3	0.6 ± 0.1
	Set 5	2.6 ± 0.3	2.0 ± 0.3	0.7 ± 0.1
	Set 10	2.7 ± 0.3*	2.1 ± 0.3	0.7 ± 0.1
Total Work (J)	All sets	1815.0 ± 542.0	1509.0 ± 501.3	1487.0 ± 398.1

Values given as repetition mean ± SD. * Significant between set differences p<0.05 within session and ** significant session differences p<0.001.

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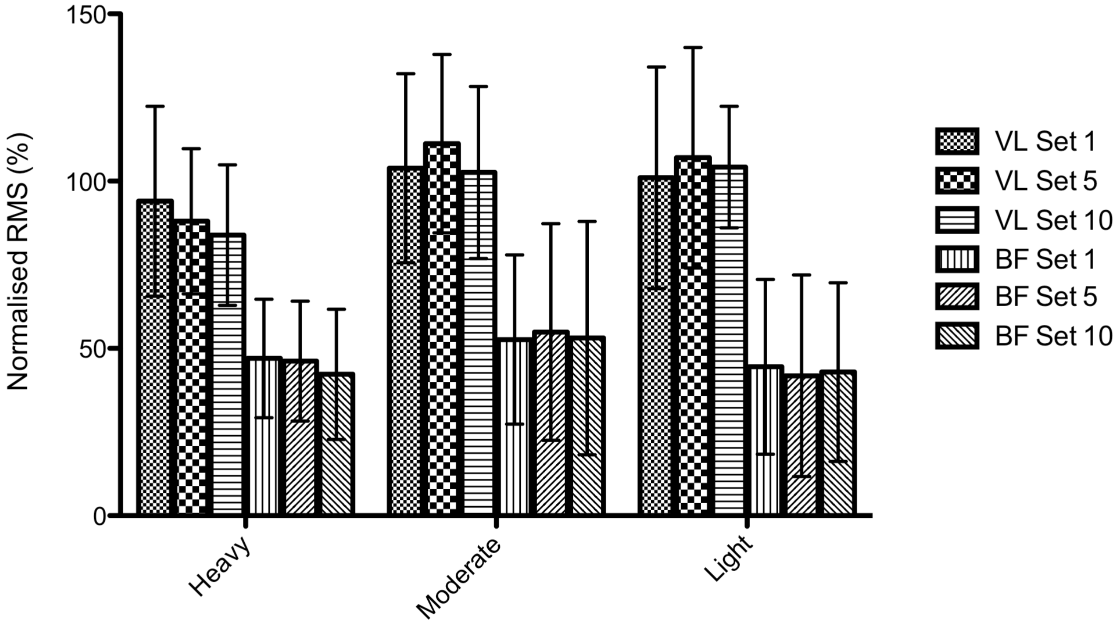

Figure 6.2. Normalised RMS amplitude of VL and BF muscles during sets 1, 5 and 10 of heavy, moderate and light sessions.
Values given as mean ± SD, n = 15. No differences for session or time in VL and BF RMS amplitude. Values are given relative to VL and BF RMS during pre-session knee extension and flexion MVC's.

6.3.2 Pre, mid and post session assessments

The absolute values for pre-, mid- and post-session NM tests are shown in table 6.3. Importantly, there were no differences between pre-session values between any variable. There was a significant time effect for absolute values of MVC ($F = 25.76$, $p<0.001$) and RFD ($F = 73.10$, $p<0.001$) across sessions and a significant interaction effect between session and time for MVC ($F = 3.68$, $p=0.01$) and RFD ($F = 4.09$, $p = 0.006$), see figure 6.3A and B. *Post hoc* tests showed that MVC significantly decreased from pre- to mid- to post- heavy session ($p<0.001$), and was significantly lower pre- to post- moderate session ($p<0.001$). There were no MVC differences found across the light session. *Post hoc* tests also revealed RFD decreased mid- and post- all three sessions ($p<0.001$). The ratio of RFD to MVC values also significantly changed across sessions ($F = 36.84$, $p<0.001$).

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Table 6.3. Pre, mid and post session assessment values from heavy, moderate and light squat session protocols.

		Heavy	Moderate	Light
MVC (N)	pre	1084.3 ± 231.2	1112.1 ± 263.3	1075.9 ± 232.6
	mid	1017.2 ± 219.6**	1050.3 ± 278.9	1046.7 ± 238.1
	post	942.9 ± 225.4**	1011.3 ± 294.4**	1044.0 ± 254.5
RMS during MVC (%)	pre	100	100	100
	mid	94.9 ± 14.2%	97.9 ± 11.2%	98.7 ± 8.2%
	post	90.5 ± 16.1%	90.6 ± 12.1%	94.5 ± 13.3
RFD ($N.s^{-1}$)	pre	6092 ± 1312	5893 ± 1214	5977 ± 1548
	mid	4762 ± 1089**	5153 ± 1344**	5233 ± 1250**
	post	4549 ± 962**	5044 ± 1384**	5265 ± 1475**
RMS during RFD (%)	pre	110.7 ± 19.9	119.1 ± 35.5	106.9 ± 29.9
	mid	88.7 ± 20.7*	104.1 ± 38.8**	99.6 ± 22.1
	post	95.0 ± 17.7	102.2 ± 26.9**	91.5 ± 22.7
RFD: MVC (s^{-1})	pre	5.64 ± 0.73	5.36 ± 0.73	5.49 ± 0.68
	mid	4.75 ± 1.09**	4.95 ± 0.86**	4.92 ± 0.49**
	post	4.94 ± 0.96**	5.04 ± 0.61**	4.91 ± 0.83**
Pt (N)	pre	31.4 ± 20.1	33.1 ± 13.3	32.6 ± 15.9
	mid	28.2 ± 215.4*	27.4 ± 13.8*	27.4 ± 11.8*
	post	23.6 ± 12.7*	25.3 ± 12.8*	26.9 ± 11.9*
dF/dt ($N.s^{-1}$)	pre	26.0 ± 18.2	26.7 ± 12.9	26.4 ± 13.6
	mid	24.8 ± 15.9	23.5 ± 12.9	23.5 ± 12.9
	post	21.5 ± 11.9*	22.2 ± 13.1*	23.6 ± 13.6*
CAR (%)	pre	95.3 ± 2.4	94.8 ± 3.1	95.8 ± 2.3
	mid	95.7 ± 2.3	94.9 ± 2.8	96.6 ± 1.8
	post	95.1 ± 3.9	95.8 ± 2.5	96.3 ± 1.7
CMJ Height (cm)	pre	48.0 ± 7.2	47.5 ± 7.0	47.1 ± 7.4
	mid	47.9 ± 7.7	47.9 ± 7.5	45.8 ± 12.5
	post	47.1 ± 7.5	46.9 ± 7.9	45.8 ± 7.5
CMJ Tf:Tc (%)	pre	84.1 ± 19.9	81.0 ± 14.1	86.5 ± 14.6
	mid	82.0 ± 16.5	78.9 ± 15.7	84.5 ± 12.6
	post	77.6 ± 16.3	77.9 ± 18.2	84.7 ± 12.5
Loaded SJ Peak Power (W)	pre	3557 ± 955	3628 ± 1013	3534 ± 1034
	mid	3543 ± 946	3741 ± 1065	3543 ± 1033
	post	3406 ± 896	3606 ± 1042	3527 ± 1020

Values given as mean ± SD pre, mid and post session, where n = 15 except for CAR and Pt where n = 9. Normalised RMS values are for the *vastus lateralis* relative to pre session RMS amplitude during MVC. Significantly different to pre-session values, * p<0.01 and ** p<0.001.

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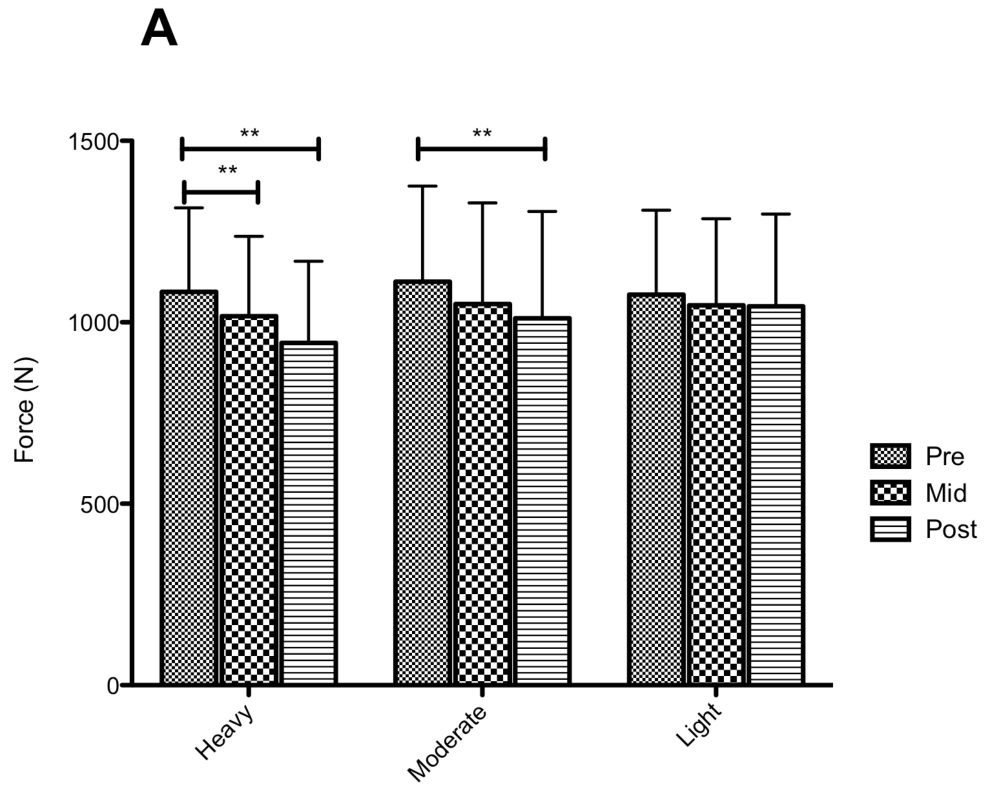

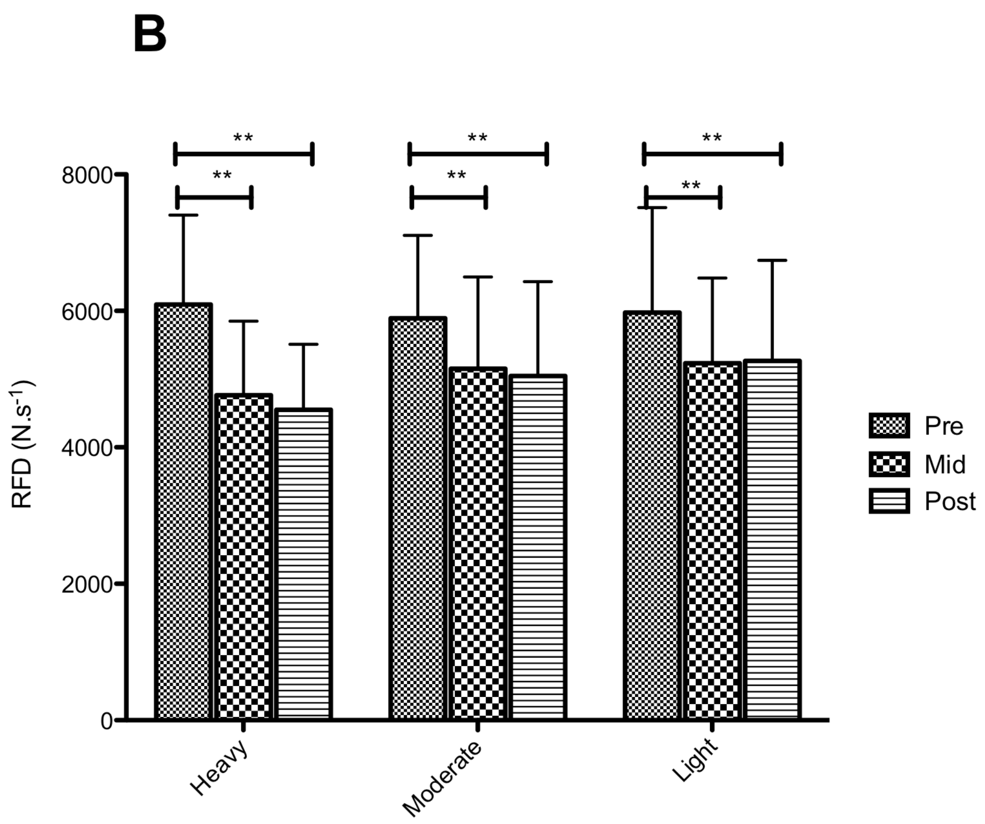

Figure 6.3. A) MVC (N), and B) RFD (N.s^{-1}) pre, mid and post heavy, moderate and light sessions. A) Mean ± SD MVC, n = 15, with session, time and session x time interaction effects found: ** Significantly different p<0.01, MVC pre versus mid and post heavy, and pre versus post moderate. B) Mean ± SD RFD, n = 15, with session, time and session x time interaction effects found: ** Significantly different p<0.01, RFD pre versus mid and post for all sessions.

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No differences were found for VL RMS during MVC, but there was a significant time difference for VL RMS during RFD (F=11.50, $p<0.001$), see figure 6.4. *Post hoc* tests revealed mid-session RMS during RFD was significantly lower than pre- heavy session ($p<0.05$), and mid- and post-session RMS during RFD were significantly lower than pre-moderate session ($p<0.001$). There were no differences found for normalised BF RMS during MVC assessments; with pre, mid and post mean ± SD values of 24.1 ± 14.2, 23.8 ± 15.5 and 21.8 ± 13.7% respectively during heavy, 22.6 ± 11.9, 26.0 ± 19.7, 24.9 ± 14.5% respectively during moderate, and 21.9 ± 13.3, 19.9 ± 13.6 and 21.0 ± 18.5% respectively during light.

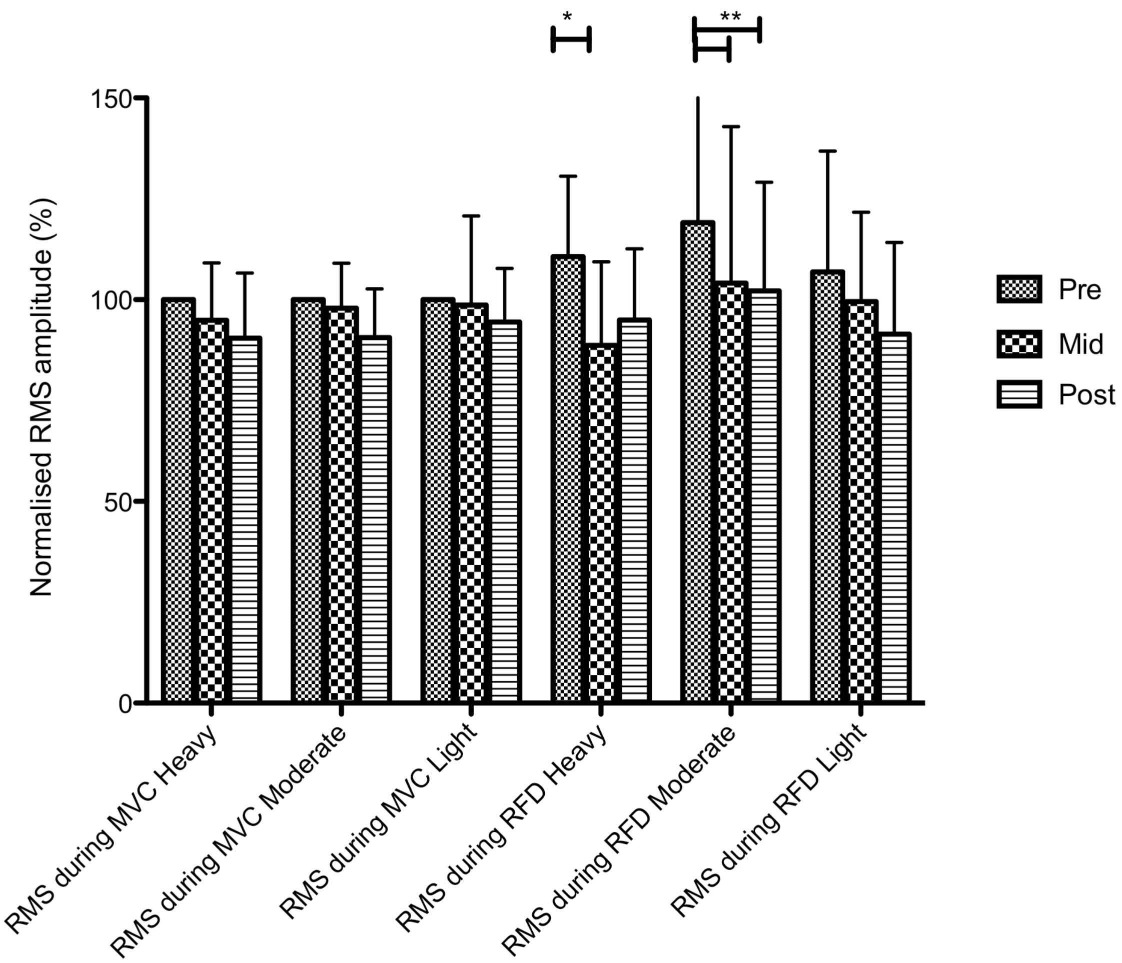

Figure 6.4. Normalised VL RMS amplitude during pre, mid and post MVC and RFD100ms tests. Values given as mean ± SD, n = 15. Normalised RMS values are for the *vastus lateralis* relative to pre session RMS during MVC. ** Significantly lower ($p<0.001$) between pre- and mid- heavy session, and between pre- versus mid- and post- moderate session.

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Pt significantly decreased across all sessions (F = 9.31, p = 0.011), where *post hoc* tests revealed significantly lower mid- (p<0.01) and post- (p<0.001) versus pre- session values. Similarly, dF/dt was significantly reduced across sessions (F = 3.71, p = 0.036) and *post hoc* tests revealed significantly lower post- versus pre-session dF/dt values (p<0.05) (see figure 6.5).

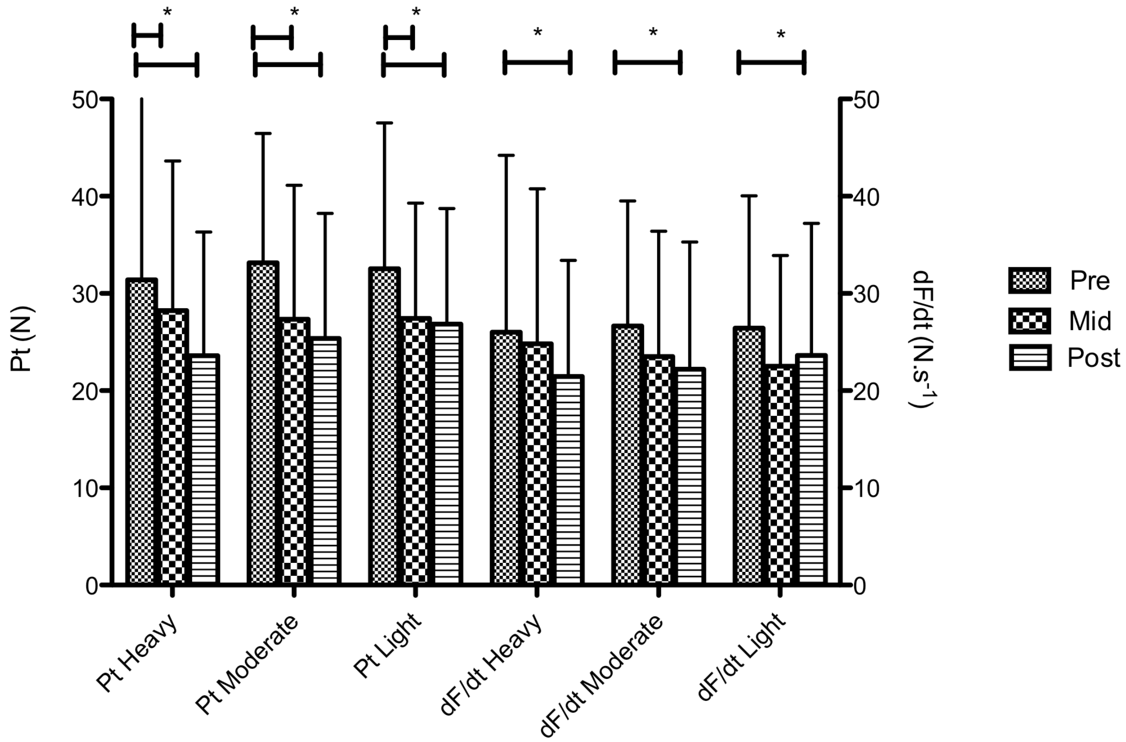

Figure 6.5. Pt (N) (left hand y-axis) and dF/dt (N.s^{-1}) (right hand y-axis), pre-, mid- and post- heavy, moderate, and light sessions.
Values given as mean ± SD, n = 9. Pt and dF/dt significant time effect found: * significant difference p<0.05 between pre versus mid and post Pt and between pre to post dF/dt.

No significant differences or interactions were found for CAR, CMJ height, CMJ Tf:Tc or loaded SJ peak power. There were significant differences between sessions for lactate (F = 64.28, p<0.001) and session RPE rating (F = 50.76, p<0.001). *Post hoc* tests revealed post lactate values were significantly different to baseline values (0.9 ± 0.3 mmol.L^{-1}) post heavy (4.6 ± 2.6 mmol.L^{-1}, p<0.001) and moderate (2.4 ± 1.5 mMol.L^{-1}, p<0.01), but not post- light session (1.5 ± 0.6 mmol.L^{-1}). Post-session RPE scores were 16.5 ± 0.9, 13.3 ± 1.8 and 11.3 ± 2.4 for heavy, moderate and light respectively.

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6.3.3 Repetition sEMG and power within sets

Figure 6.6A shows a significant session by set interaction effect for repetition VL RMS ($F = 6.27$, $p<0.001$). *Post hoc* tests revealed that during the heavy session repetitions four ($p<0.05$) and five ($p<0.01$) were significantly greater than repetition one, during the moderate session repetition five ($p<0.01$) was significantly greater than repetition one, and during the light session, repetition VL RMS was unchanged.

Figure 6.6B, shows significant repetition power session by set ($F = 4.28$, $p = 0.002$) and a significant session by repetition interaction effects ($F = 8.12$, $p<0.001$). *Post hoc* tests revealed that during the heavy session repetition power was unchanged during set one, that repetition five was lower than one during set five ($p<0.01$), and that repetitions four and five were lower than one during set 10 ($p<0.001$). There were no differences in repetition power values found during the moderate or light sessions.

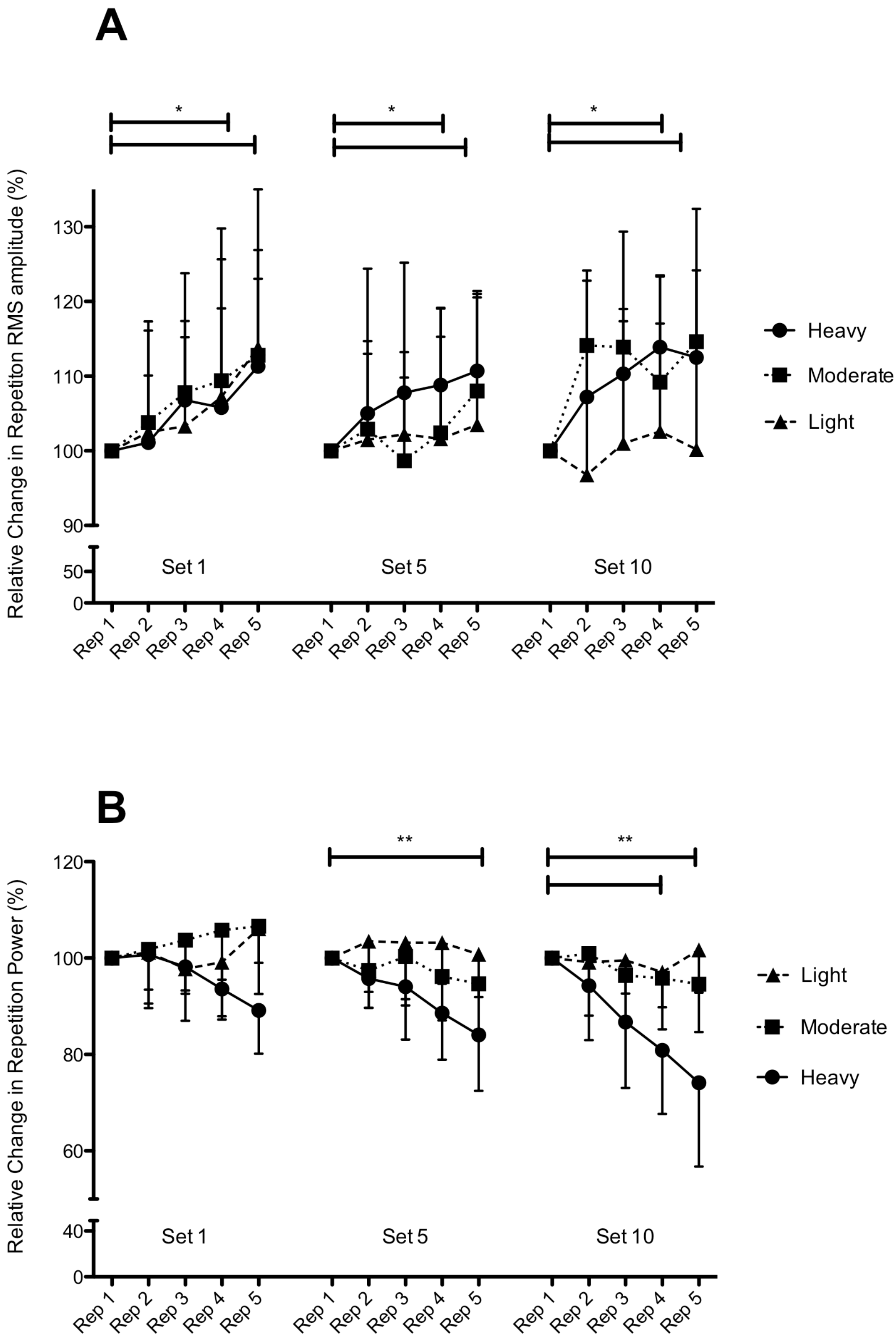

Figure 6.6. A) VL RMS amplitude and B) power, relative to repetition one (%) within sets 1, 5 and 10 of heavy, moderate and light sessions.

Values given are the mean ± SD relative to repetition one of each set, n = 15. A) RMS amplitude repetition and session x set interaction effects found: * significant difference $p<0.01$ between repetitions 1 and 4 & 5 during heavy and between repetitions 1 and 5 during moderate sessions in VL RMS. B) Power repetition, session x set and session x repetition interaction effects found: ** Significant difference $p<0.001$ in power between repetitions 1 and 5 during set 5 and between repetitions 1 and 4 & 5 of set 10 of the heavy session.

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6.3.4 Testosterone and Cortisol findings

There was a significant session by time interaction effect for T ($F = 3.0$, $p = 0.03$). *Post hoc* testing revealed no differences between baseline, mid- and post- heavy and moderate sessions, but baseline T was significantly higher than mid- and post- light session ($p<0.001$). Cortisol (C) ($F = 81.64$, $p<0.001$) and T:C ratio ($F = 40.35$, $p<0.001$) were both significantly different across all three sessions. The mean ± SD baseline T of the four female subjects was 77.15 ± 20.09 $\mu g.ml^{-1}$ and was 144.69 ± 70.09 $\mu g.ml^{-1}$ for the 11 male subjects. Ten subjects provided hormone samples during the familiarisation trial to compare the changes due to the sessions with the naturally occurring changes expected during the same time of day. The mean ± SD baseline and post familiarisation T values were 166.01 ± 96.59 and 122.35 ± 66.21 $\mu g.ml^{-1}$ respectively. The mean ± SD baseline and post familiarisation C values were 3.8 ± 1.2 and 2.1 ± 1.0 $ng.ml^{-1}$ respectively.

No relationships were found between T, and T:C and relative post-session MVC, RFD or CMJ height values.

Table 6.4. T, C and T:C data at baseline, mid and post heavy, moderate and power sessions.

		Heavy	Moderate	Light
Testosterone ($\mu g.ml^{-1}$)$	Baseline	102.8 ± 73.2	119.7 ± 94.7	146.8 ± 80.5
	Mid	98.6 ± 57.3	88.3 ± 45.3	86.2 ± 16.9
	Post	92.6 ± 69.6	87.2 ± 54.3	85.8 ± 20.9
Cortisol ($ng.ml^{-1}$)**	Baseline	4.4 ± 2.4	3.8 ± 2.4	4.5 ± 1.3
	Mid	2.1 ± 1.0	2.2 ± 1.5	2.4 ± 1.1
	Post	2.1 ± 0.9	1.7 ± 0.9	1.8 ± 0.6
T:C ratio**	Baseline	31.2 ± 29.2	46.2 ± 38.1	39.6 ± 19.7
	Mid	60.0 ± 40.6	49.9 ± 36.6	49.9 ± 36.6
	Post	50.9 ± 35.2	58.6 ± 41.9	58.6 ± 41.9

Values given as mean ± SD, n = 11 $ significant interaction p<0.05 between session and time for T, ** significant time difference p<0.001 for C and T:C.

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6.3.5 Relationships between strength level and post session response

No relationships were found between relative system mass squat load and relative post-session MVC, RFD or CMJ height values. Normalised MVC force was related to relative post MVC ($r = 0.59$, $p = 0.018$) and relative post CMJ height ($r = 0.65$, $p = 0.008$) for moderate but not heavy or light sessions (see figure 6.7).

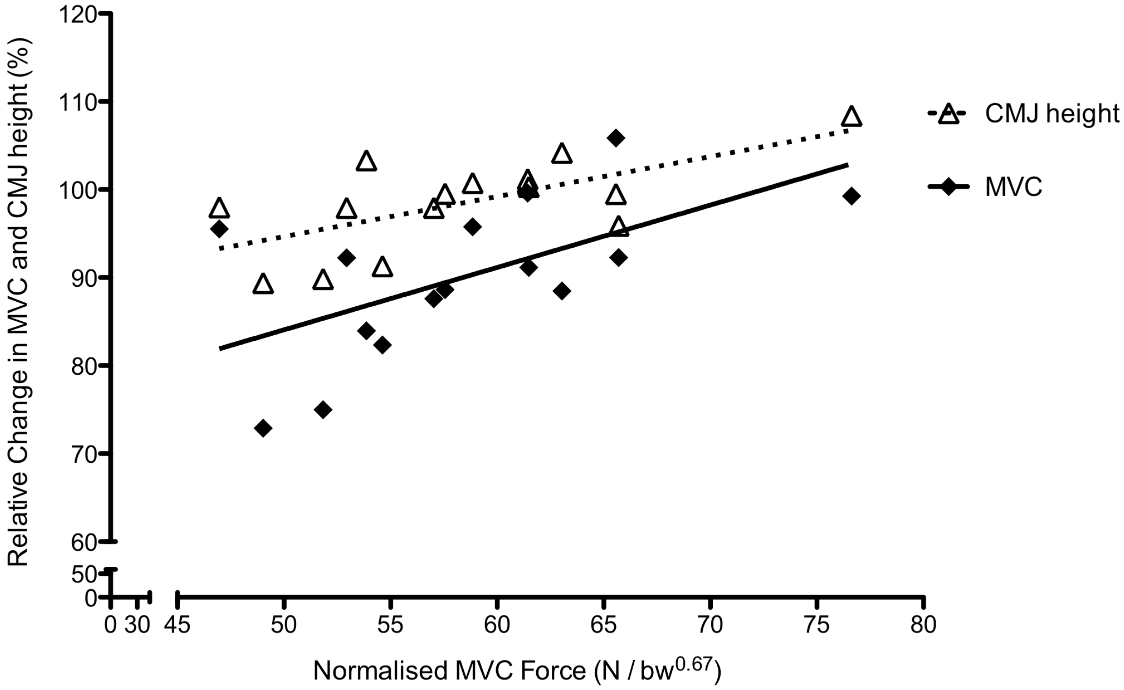

Figure 6.7. Relationship between normalised MVC force and relative post CMJ height, and relative post MVC, following the moderate session.
Significant relationship between relative post MVC = 0.486 + 0.007 N / $bw^{0.67}$, $r^2 = 0.359$, $p = 0.018$ and relative post CMJ height = 0.712 + 0.00469 N / $bw^{0.67}$, $r^2 = 0.429$, $p = 0.008$.

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6.4 Discussion

The high intensity squat exercise at heavy, moderate and light loads resulted in different mechanical power outputs, repetition duration and impulse values, but similar total work and quadriceps (VL) and hamstring (BF) sEMG amplitude. MVC decreased the most during and following the heavy session (-6% and -13% mid- and post-session respectively), with slightly less decrease following the moderate session (-10% post). There was no change (-3%) following the light session. Importantly, there were no changes in BF RMS during MVC tests. Therefore, MVC force values were independent of antagonist muscle changes. Similar to MVC, RFD decreased most following heavy (-25%), then moderate (-15%) and light (-11%). The different post-session force generation decreases are consistent with the different post-session blood lactate responses. These differences occurred despite similar total work and similar muscle activity levels, along with high intensity explosive execution in all sessions. Therefore, as expected, load intensity determines the NM response to explosive squat exercise. Consequently, in terms of the mechanical variables, exercise impulse and not power best reflects the demand of the high intensity sessions.

Pt was reduced mid- and post- all sessions and dF/dt was also reduced post- each session. Pt is considered to represent excitation-contraction coupling (Hill *et al.*, 2001) as the net outcome of post-activation potentiation and fatigue, whilst dF/dt may more closely represent potentiation, independent of fatigue (Fowles & Green, 2003). Therefore, reduction in both variables supports contractile fatigue 10 minutes following the sessions. However, evoked twitch force values were small, relative to MVC, which may limit conclusions based upon these findings. Fatigue related to excitation-contraction coupling tends to result from the repetitive dynamic contractions (Jones, 1996). There were no changes in any session found in CAR, which represents central activation of the NM

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system. Following chapter five, it seems that reduced force generation capacity post high intensity squat exercise, is most likely related to peripheral fatigue (Kent-Braun, 1999). This finding was contrary to the expectation that central fatigue would be observed following the heavy session, based upon the neuromuscular demand of lifting high load explosively (Ives & Shelley, 2003). It is possible that high intensity resistance exercise has an excitatory effect upon the central nervous system, possibly at a cortical level (Taylor *et al.*, 1996). However, the CAR assessment does not distinguish between efferent excitatory drive and afferent inhibition mechanisms, both of which influence motor neuron firing and subsequent motor unit activation (Gandevia, 2001). This reinforces the suggestion from chapter five, that resistance exercise sessions associated with chronic adaptation are not necessarily dependent upon acute central fatigue. This is contrary to previous conclusions based upon reduced sEMG amplitude in post session MVC's (Hakkinen, 1994, 1995; Linnamo *et al.*, 1998; McCaulley *et al.*, 2009). However, these conclusions were limited (Perrey *et al.*, 2010), as peripheral factors at the NM junction may influence the sEMG signal (Fitts, 1994; K. Matsuda *et al.,* 1999). Lack of evidence of central fatigue may have been due to the timing of the tests (Sogaard *et al.*, 2006; Taylor *et al.*, 1996), as CAR values can recover within minutes post exercise (Behm & St-Pierre, 1997). Perhaps the intermittent structure of resistance exercise, with sets interspersed with rest, attenuates the central fatigue that is shown in continual maximal exercise tasks (Taylor *et al.*, 1996). Furthermore, perhaps a very high volume of sub-maximal resistance exercise is required to induce central fatigue, as this is most likely to occur following endurance exercise (Bentley *et al.*, 2000; Kay *et al.*, 2001) and very prolonged contractions (Behm & St-Pierre, 1997).

No significant reduction in power was found during the loaded squat jump assessment. This is also perhaps surprising, given the changes in RFD and MVC during isometric knee extensions. It suggests that less NM fatigue occurred during the performance of the

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dynamic multi-joint movement than in an isometric test of a constituent muscle. This may be explained by a possible rise in muscle temperature following each session, helping to maintain power generation (Racinais *et al.*, 2005); particularly as temperature has greater influence on dynamic shortening contractions in comparison to isometric force generation (Ranatunga, 2010). The loaded SJ showed a tendency to be reduced post session ($p = 0.06$). Therefore, it is possible that another multi-joint power test with less variability, such as machine based squat jumps, would be have elicited significant findings.

RFD decreased more than MVC following each session, demonstrated by a reduction in the RFD:MVC ratio (Tillin *et al.*, 2010). A previous study also found greater decrement in the initial period of RFD compared to MVC following high intensity moderate load squat exercise (Chui *et al.*, 2004). This was explained by reduced Ca^{2+} re-uptake affecting time limited force generation, in comparison to prolonged and possibly higher frequency force generation during MVC. During the latter, the Ca^{2+} saturation required for cross bridge formation may not be limited (Fowles & Green, 2003). Furthermore, RFD was decreased at the mid- and post-session assessments, suggesting five sets of high intensity resistance exercise was sufficient to reduce RFD in comparison to maximal force generation capacity. Reduced RMS during RFD assessment, but not during MVC, may explain this. This suggests that rapid initial motor unit activation, critical for RFD was reduced (Aagaard *et al.*, 2002a; Van Cutsem *et al.*, 1998). This may also indicate changes in central activation. However, RMS during RFD was only reduced mid- heavy session and mid- and post-moderate session. In addition, the methods are not able to distinguish between possible central or peripheral causes of reduced sEMG amplitude (Perrey *et al.,* 2010). Nonetheless, a greater reduction in RFD, in comparison to MVC has functional significance for training activities that require explosive power or force generation (Thorlund *et al.*, 2008). For example, even the light session resulted in a decrease in RFD,

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despite no change in MVC and lactate. Coaches should be aware that a limited volume of high intensity resistance exercise affects RFD, even without obvious signs of fatigue.

The greatest increase in repetition VL RMS occurred within sets of heavy, and then moderate high intensity squats. There was no increase during the light session. In addition, repetition power decreased within sets of the heavy session only. This decreased further as the heavy session progressed. In contrast, power was maintained, across and within sets, during moderate and light sessions. This suggests the fatigue in performance (reduced power) during sets of heavy high intensity squats led to greater compensatory additional motor unit recruitment (Adam & De Luca, 2005; Dias da Silva & Goncalves, 2006). Moderate load high intensity squats did not lead to acute performance fatigue during sets, but in order to maintain power, additional motor unit recruitment occurred. There was no significant repetition response during the light session. Increased sEMG amplitude during sustained contractions is associated with sub-maximal contractions (Moritani *et al.*, 1986). This suggests, that despite explosive execution of the loads, high intensity squat exercise is not truly maximal, in NM activation terms. Therefore, the increased sEMG amplitude during training sets may be critical for maximum strength and power adaptation (Takarada, Takazawa, *et al.*, 2000), otherwise full activation of the larger fast twitch motor units may not occur. This suggests moderate and heavy load high intensity squats would be effective training exercise. In contrast, despite involving the highest power outputs, light explosive squats may not provide sufficient NM stimulus.

It was hypothesised that strength levels would not influence the post- moderate and light session NM responses, because moderate and light session loads were set in system mass terms, relative to heavy session load. In support of this, squat load lifted (relative to body mass) was not related to any post- session MVC, RFD or CMJ height, relative to pre-

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session values. This contrasted with the finding from chapter five, where the power session loads were not determined with system mass. However, squat load is a functional measure that represents individual strength level. Alternatively, the normalised MVC force is a direct measure of relative strength. This was positively related to post-session MVC and CMJ height following the moderate session, but not post- heavy or light sessions. This suggests individual strength level may influence the moderate session response, which was contrary to the hypothesis. Increased jump performance has been demonstrated following squat exercise, especially for stronger subjects (Mangus *et al.*, 2006; Ruben, Molinari, Bibbee, Childress, *et al.*, 2010). However, increases in MVC are not normally associated with the post-activation potentiation response (Tillin & Bishop, 2009) and contradict the reduced Pt and dF/dt findings following each session. Further study may be required to assess the NM response to power type sessions using system mass loads relative to true maximal values and not subjectively determined RPE load levels. The possibility of post-activation potentiation for the strongest athletes following explosive moderate load exercise was further explored in a subsequent case study using two elite male sprinters. They performed eight sets of explosive barbell exercise in the afternoon following a high volume sprint running session. Both subjects benefited from increased MVC, CAR, and CMJ, post- explosive barbell session relative to post- running session. This increase was maintained the following morning. The methods and results are summarised in *Appendix 6*.

The secondary aim of this study was to investigate the acute hormonal response, and its possible relationship to NM response. T reduced over the course of the light session, relative to baseline measures, but did not during heavy and moderate sessions. C reduced as expected with circadian rhythms across all sessions. Previous findings suggest that both resistance exercise load and volume influence post T response (Crewther, Keogh, *et al.*,

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2006). Less research has analysed the hormonal response following high intensity (explosive) resistance exercise (Pullinen *et al.*, 1998). The present study does not support 10 sets of high intensity squat exercise as having a positive influence upon T levels. However, the current findings may be confounded by the comparison between post-session and baseline samples, which contrasts typical methods that compare immediately pre- and post- session values (Crewther, Keogh, *et al.*, 2006). However, data taken from the familiarisation session, showed T values reduced with no exercise across the corresponding morning period, following established hormonal rhythms (Bird & Tarpenning, 2004). Therefore, perhaps the heavy and moderate load sessions actually increased T above naturally reducing values. In comparison, the light session had no effect. This conclusion is speculative, but may suggest greater possible stimulus for adaptation following heavy and moderate load explosive training.

The present study found no relationship between post session NM and T responses. This is contrary to previous suggestions by Bosco *et al.* (2000) relating NM and hormonal responses, and evidence that acute T response may influence NM performance, such as power (Cardinale & Stone, 2006; Crewther *et al.*, 2011). The present data is supported by research showing that T has a positive influence upon leg strength, but not upon leg exercise fatigue (Storer *et al.*, 2003). To definitively ascertain whether T attenuates fatigue during strength sessions, research comprising trials comparing natural to blocked T responses is required (Kvorning *et al.*, 2007).

6.5 Summary and Conclusion

Overall, the findings show that NM fatigue is proportional to load during high intensity sessions with similar total work, muscle activity and session volume. The reduction in force generation capacity, the increased repetition RMS during sets and post session

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lactate, were all greatest following heavy, then moderate and then light sessions. Only the heavy session resulted in performance fatigue (reduced repetition power) during sets of high intensity squats. RFD reduced comparatively more than MVC across all three sessions, suggesting RFD is strongly influenced by high intensity resistance exercise, even those comprising relatively light loads. No change in CAR, reduced Pt and greater RFD compared to MVC, following all three sessions, points to peripheral fatigue mechanisms, namely excitation-contraction coupling dysfunction, as the reason for reduced force generation capacity. The findings suggest that the combination of high load and high intensity resistance exercise, such as heavy explosive squats, ensures a very good stimulus for NM adaptation. This is based upon the increased NM activation that occurred during sets of heavy and moderate explosive squats. However, moderate load explosive exercise may provide a beneficial stimulus, but with less acute NM fatigue. Therefore, athletes may recover faster following moderate load explosive training. The findings question the efficacy of light load explosive type exercise in comparison.

No relationship was found between individual squat load and post session MVC and CMJ following any session. However, individual normalised force levels were related to post MVC and CMJ following the moderate session only. Therefore, the hypothesis that NM response to system mass controlled load in the moderate and light sessions would not be influenced by strength levels was only partly upheld. Further study is required to definitely assess the influence of strength level on NM fatigue. The greatest T response occurred following the heavy session, as expected, with no change in T levels relative to natural circadian rhythms following the light session. No relationship was found between acute T and acute NM response post session, suggesting acute hormonal response has little affect upon acute NM fatigue.

Chapter Seven

Thesis Summary and Conclusions

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7 Thesis Summary and Conclusions

This thesis has used methods from previous neuromuscular (NM) research of single bouts of exercise, typically to fatigue. These methods comprised a NM assessment battery to analyse changes following exercise along with electromyography (sEMG) and power analysis during exercise. These were used to conduct novel comparative investigations of entire structured sessions of maximum strength and power type resistance exercise.

The first study was conducted to establish the reliability of a combined biomechanical and sEMG analysis system during barbell squat exercise. This was to ensure accurate measurements were possible to monitor muscle activity and exercise performance during the subsequent investigations. The system comprised synchronised recordings of knee angle from a flexible electrogoniometer, displacement data from a cable extension linear position transducer attached to the barbell, and sEMG root mean square amplitude (RMS) from the *vastus lateralis* muscle. Displacement data was derived into mean power of the concentric phase of the squat exercise. Well-trained weightlifting subjects performed barbell squat exercise at 50%, 75% and 100% of 3RM squat load, on three separate trial days. Results demonstrated good reliability for all three measurements (CV < 10%). In comparison to previous studies of static knee angle measurements and isometric quadriceps contractions, this study provided novel reliability data for electrogoniometry and RMS measures during dynamic barbell squat exercise. Furthermore, knee angle and barbell displacement were positively related ($r^2 = 0.82$), suggesting the kinematics of the whole squat movement were accurately represented by knee joint motion. It was concluded that the analysis system was robust and suitable for monitoring sEMG and mechanical power during dynamic barbell exercises.

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The second study investigated the reliability and response to incremental load and fatigue of directly measured muscle fibre conduction velocity (MFCV) during barbell squat exercise. Well-trained subjects performed isometric knee extensions at 50%, 75% and 100% of MVC force, barbell squat exercise at 50%, 75% and 100% of 3RM load and squat jumps at 50% 3RM load until failure. Inter-trial day reliability was established for MFCV at CV = 9.6%. Significantly different *vastus lateralis* RMS and MFCV was shown between isometric force levels, whilst only RMS differed across dynamic squat load levels. Mean power output significantly declined at the end of the fatiguing squat jump trial, along with MFCV, whilst RMS was unchanged. This suggested MFCV indicated acute peripheral fatigue processes occurred, whilst the net effect of any changes in motor unit recruitment and firing rate upon the sEMG signal amplitude was constant. Together these findings suggested MFCV is reliable and sensitive to fatigue. It was concluded that MFCV, alongside RMS, provided useful information in the analysis of acute NM response.

The following three studies investigated NM responses during sessions of maximum strength and power type resistance exercise sessions. Specific session comparisons were conducted to investigate the affect of exercise, load and contraction velocity on NM response. The purpose was to further understanding of the possible stimulus for adaptation, fatigue mechanisms and recovery.

The first study compared the NM response to a maximum strength type session, of squat versus deadlift barbell exercise, in well-trained male subjects. The RMS, MFCV and mechanical measures established in the first two studies were used to monitor repetition responses to five sets x five repetitions; alongside NM function assessments pre- and post-sessions. The squat and deadlift were matched for relative load intensity, muscle activity (*vastus lateralis* RMS) and concentric movement speed, ensuring analysis solely compared

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the mechanical difference between the exercises. Firstly, repetition RMS increased during both exercise sessions, whilst MFCV was reduced in squat sessions only. However, repetition power was maintained within and across all five sets in both sessions. This suggested the task of maintaining force generation during un-supported whole body barbell exercise led to additional motor unit recruitment, similar to previous findings of submaximal isometric contractions. However, this was only associated with acute peripheral fatigue during sets of the squat session, based upon the MFCV data. The difference in exercise response was explained by longer repetition duration, or greater work, during the squat. Secondly, there were minimal changes in NM function post- squat and deadlift sessions. This suggested performing a maximum strength type session, with a volume of five sets, does not result in decreased force generation capacity in elite subjects. Consequently, the stimulus for adaptation is perhaps indicated by the increased muscle activation during the repetitions, and may not be dependent upon acute NM fatigue.

The second investigation compared the NM response and 24-hour recovery following 12 sets of maximum strength versus power type sessions, performed by elite male and female sprinters. A typical elite training session structure, comprising Olympic-style barbell exercises was assessed. The main finding was reduced force generation capacity following both sessions, indicated by decreased isometric knee extension force (MVC) and evoked twitch force (Pt) assessments. However, there were greater decreases following maximum strength versus power session. Relative post-session MVC was -11% & -6% and Pt was -18% & -10% in maximum strength and power sessions respectively. This was explained by the greater work performed during maximum strength sessions. Interestingly, there was no change in superimposed stimulated force (CAR), or RMS during the post-session MVC force assessments. Contrary to previous studies with limited methodology, the reduced Pt but maintained CAR suggests peripheral, and not central fatigue mechanisms explain the

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reduced force generation capacity found. Furthermore, the evidence for peripheral fatigue implies chronic NM adaptation to maximum strength and power type training is not related to the acute central fatigue resulting from sessions. Following the previous study, increased repetition RMS was also found within sets during both protocols. This further supports the increased muscle activation during resistance exercise as the key indicator of NM stimulus. There were no significant changes NM function 24-hours post- either session, suggesting NM recovery was complete in this time. Further analysis revealed possible differences in fatigue between male and female subjects post- power session. However, this was best explained by the variation in system mass load used by subjects during the power session, relative to maximum strength session load. This was an unexpected, but practically useful finding. It suggests load levels used during barbell exercise power sessions should be calculated in system mass terms.

The final study compared the NM and hormonal response to high intensity 'explosive' type resistance exercise performed using heavy, moderate or light loads. Elite power athletes performed trials of 10 sets x five repetitions of explosive barbell squats, on separate days, at each load level. Moderate and light session used 75% and 50% of maximum strength load, in system mass terms, following the previous study's finding. *Vastus lateralis* and *biceps femoris* RMS and total work were comparable across sessions, with mean power greatest during the light session. MVC peak and rate of force development (RFD) assessments significantly reduced post session, with the greatest decrement post- heavy, then moderate and then light sessions. This was associated with greatest repetition power decrease and repetition RMS increase within sets of the heavy and then moderate sessions, with minimal changes during the light session. Therefore, NM fatigue following high intensity explosive exercise is related to load and not power. In addition, greater stimulus for NM adaptation may result from heavy and moderate explosive squats. However,

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moderate load results in less NM fatigue, which may be advantageous. In addition, RFD decreased more in comparison to MVC across all sessions, and was significantly reduced after 5 sets (mid-session). Pt was also reduced following all high intensity squat sessions, whilst CAR did not change. This reinforced the previous findings that peripheral fatigue mechanisms result from maximum strength and power type sessions. The findings demonstrated the hormone response post- light session was less than heavy and moderate session. This also implied less potential adaptation stimulus from the low load in comparison to higher load explosive resistance exercise. No relationship was found between post-session testosterone and NM responses, suggesting acute hormonal status does not influence NM fatigue.

The following conclusions, addressing the main thesis aims are drawn from the findings: Firstly, what is the NM response during and following whole sessions of maximum strength and power type resistance exercise? Specifically, what differences in NM response exist between exercises and between different types of maximum strength and power sessions?

During high intensity resistance exercise performed ‘explosively’, *i.e.* high voluntary effort, power reduces within sets of five repetitions. This is accompanied by increased motor unit recruitment. This is the typical isometric sub-maximal NM response and is proportional to the exercise load. The response may further increase as the session progresses. During high load, maximum strength type exercise, performed with controlled movement speed, a similar NM response occurs. However power is maintained in these conditions, suggesting increased muscle activation results from maintaining force generation during dynamic repetitions. This is possibly related to barbell lifting tasks, involving the support of load and control of posture. The same NM response also occurs during relatively light load power type exercises. However, power type exercise results in

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a smaller increase in repetition muscle activation, in comparison to within sets of maximum strength exercise. The consistent increase in motor unit recruitment found may indicate the NM activation stimulus required for chronic adaptation. If so, then high load and/or high intensity explosive-type resistance exercise may provide the optimal training stimulus.

Following maximum strength type sessions force generation capacity reduces in proportion to the volume of training. Five sets of maximum strength exercise results in a small decrement in force generation capacity, whereas as 10-12 sets results in >10% decrement. Importantly, rate of force development capacity is affected more in comparison to peak force, which has implications for athletic performance. The recovery of force generation capacity may take up to 24-hours to return to pre-session levels. In comparison, power training results in a smaller decrement of force generation capacity, but this is dependent upon relative load level used. Specifically, power sessions comprising no more than 50% of maximum strength session load, in system mass terms, result in minimal fatigue. In contrast, power sessions using 65-75% of relative load may result in significant force decrement in the range of 5-10%. The practical significance is that coaches need to plan the timing and recovery of maximum strength versus power sessions differently within weekly programmes, and use system mass to determine power session loads.

Secondly, what is the nature of neuromuscular fatigue following maximum strength and power training?

Following resistance exercises sessions it was found that MVC force reduced, along with Pt but not CAR assessments. This suggests peripheral factors cause acute NM fatigue following maximum strength and power training of sufficient volume and/or intensity.

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The excitation-contraction coupling mechanism is the most likely location of this peripheral fatigue. Little evidence was found that central fatigue occurred following maximum strength and power training. This suggests the NM stimulus for chronic adaptation is not dependent upon acute nervous system fatigue, contrary to previous conclusions. However, the direct relationship between the acute NM response and chronic adaptation was beyond the scope of these investigations. This type of study would be very important for further understanding of maximum strength and power adaptation. Also it would be useful to explore the influence of individual differences upon NM responses to different types of session, as the ability to identify these may assist coaches and athletes optimise training programmes.

In general, the thesis has a number of strengths in comparison to previous research investigating strength and power training. In particular, a comprehensive NM assessment battery was used that allowed accurate interpretation of the mechanisms of fatigue. However, assessing NM function at various time points following the sessions could have strengthened the methods further. This would have provided more detailed information on recovery following resistance exercise, and possible variation between peripheral and central factors. In addition, further evoked twitch or tetanic assessments evoking higher force values may have measured the peripheral fatigue processes with greater accuracy and detail.

Importantly, elite subjects were used and the resistance exercise session protocols assessed were representative of elite training practises, whilst at the same time providing scientific controls. In addition, the barbell exercises assessed ensured NM responses were specific to tasks performed by athletes in training. However, a possible weakness was the use of mixed sex subject groups.

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Strength and conditioning specialists and sports coaches may consider the following as recommendations of how to apply the findings and conclusions from this thesis:

1) The degree of NM fatigue following typical maximum strength sessions is significant and may take 24 hours to recover if 10 or more sets of intense exercise are performed. This seems to be regardless of individual strength level.
2) To limit fatigue following maximum strength training, no more than five sets of intense exercise should be performed.
3) The degree of fatigue following power training is less significant and can be minimal. This is dependent upon power loads being relatively light (50%) in comparison to maximum strength loads in system mass terms.
4) As a general rule, intensive maximum strength sessions are best performed after other training activities, and possibly preceding recovery days within a programme.
5) Resistance exercises involving high load and/or high intensity 'explosive' execution may provide an excellent neuromuscular stimulus, due to the increasing muscle activation occurring within sets. However, to avoid acute fatigue within sets, a limit of three repetitions should be performed.
6) System mass should be used to plan relative loading levels, particularly of power type exercises to ensure parity between athletes. System mass should also be used to monitor training load, to ensure all the work performed is accounted for.
7) Post activation potentiation following entire sessions may be possible, but must be tested for each individual athlete and each session type. High intensity, moderate load sessions are likely to result in potentiation in strong athletes.
8) Selecting exercises with lower mechanical work and/or impulse may reduce the acute NM fatigue response.

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8 Appendices

Appendix 1: Elite Strength and Conditioning Coach Survey

Results of a survey of 29 strength and conditioning coaches employed by the English Institute of Sport working with international standard senior athletes of Olympic and English sports. The survey was focused upon three areas, 1) the type of sessions using barbell exercises, 2) the method for controlling load or intensity of exercises and 3) exercise choices.

1. How frequently do you utilise barbell exercises with different session types?

	Often	Sometimes	Never
Max strength	90%	10%	0%
Power – explosive	76%	24%	0%
Power – speed	3%	90%	3%
Hypertrophy	34%	14%	48%

2. How do you control loading or intensity during sessions?

	Often	Sometimes	Never
Sets performed to repetition maximum (all sets to fatigue)	0%	3%	97%
Sets performed to target load (% of RM not to fatigue)	24%	69%	3%
Progress sets through series up to a target load (some sets performed to RM)	41%	45%	10%

3. Which of the following exercises do you include regularly in programmes?

Squat – heavy loaded	93%
Deadlift – heavy loaded	48%
Split Squat – heavy loaded	52%
Push Press – heavy loaded	24%
Squat – speed – light loaded	24%
Split squat – explosive – light loaded	45%
Squat explosive – light/moderate loaded	62%
Jerks	31%

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Appendix 2: Squat, Deadlift, Split Squat, Push Press Images

Figure A2.1. Barbell Squat.

Figure A2.2. Deadlift.

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Figure A2.3. Split Squat.

Figure A2.4. Push Press.

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Appendix 3: Post strength exercise Lactate sample pilot study

Aim:

To determine the timing of lactate sampling post strength exercise to obtain peak values.

Methodology:

On 23rd May 2008 at 2 pm, two male S&C coaches (aged 29 & 35 years, body mass 86 & 88 kg) completed a warm up followed by squat training sessions. The warm comprised of 10 minute cycling, followed by two minutes seated rest whilst resting lactate was taken. Subjects then completed three to four sets of light barbell exercises, followed by the five sets x five repetitions squat training session. Lactate was recorded after the end of the fourth and final set and every minute thereafter for six minutes. The data is presented.

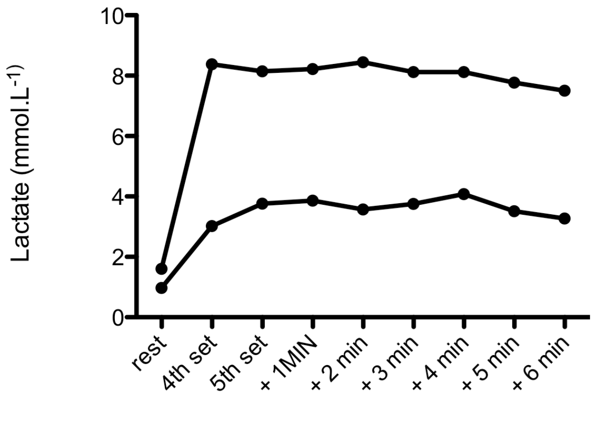

Figure A3. Blood lactate concentration within and following 5 sets x 5 reps of squat.
Values shown are the responses from each subject.

Summary:

Both subjects increased lactate from post warm up resting values, but had quite different responses in terms of magnitude, but similar response in terms of time. In the seated and stationary position it would seem that peak lactate is found between one and four minutes post strength exercise. We propose that taking samples between two and four minutes after the final set of exercise is appropriate to ensure peak lactate post resistance exercise is achieved.

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Appendix 4: CAR, MVC, CMJ reliability

Aim:

To present reliability of measures from CAR, MVC and CMJ height variables obtained during the studies in chapters four and five.

Results:

Table A4 shows the results of inter-trial day reliability of CAR, MVC and CMJ height: giving typical error, coefficient of variation (%) and intra-class correlation (r), n = 19. Mean ± SD values for each variable were CAR = 94.7 ± 3.8%, MVC = 1050.3 ± 249.0N, CMJ = 47.1 ± 7.5cm.

Summary:

Good reliability was found for each variable during the studies in this thesis.

Table A4. Typical error, CV and ICC for CAR, MVC and CMJ height.

Typical Error	CAR (%)	2.6
(n = 19)	MVC (N)	44.1
	CMJ (cm)	2.6
CV (%)	CAR	2.9
(n = 19)	MVC	4.3
	CMJ	5.2
Intraclass correlation (r)	CAR	0.540
(n = 19)	MVC	0.970
	CMJ	0.881

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Appendix 5: Relationships between the change in MVC, load and sEMG amplitude post squat and deadlift sessions.

The following data from chapter four is presented in addition to the results presented in chapter four. This particular analysis was not part of the original research aims of the study, however it is of potential interest to strength and conditioning coaches.

Summary of findings:

An interaction effect between squat and deadlift sessions and time for MVC force was found ($F = 5.90$, $p = 0.041$). Following the squat session MVC was reduced and following deadlift session MVC was increased. Specifically, six subjects had reduced MVC force compared to pre-squat session values, whereas following deadlift session eight of the nine subjects had relatively higher MVC. Further analysis of the data was performed to help explain this finding. Figure A5, shows the significant relationship found ($r^2 = 0.51$, $p = 0.03$) between deadlift load lifted, in kilograms, and the relative change in MVC post the deadlift session: where, relative MVC post deadlift (%) = 79.9 + 0.147 x deadlift load (kg). In contrast there was no significant relationship between the relative change in MVC post squat session and squat load lifted.

Significant correlations between normalised RMS amplitude and the load lifted during repetitions of deadlift and squat were found ($r = 0.86$, $p<0.01$ and $r = 0.80$, $p<0.01$ for deadlift and squat respectively. Interestingly, there was a significant inverse relationship between the maximum knee angle and the normalised RMS amplitude during the deadlift ($r = -0.72$, $p<0.05$).

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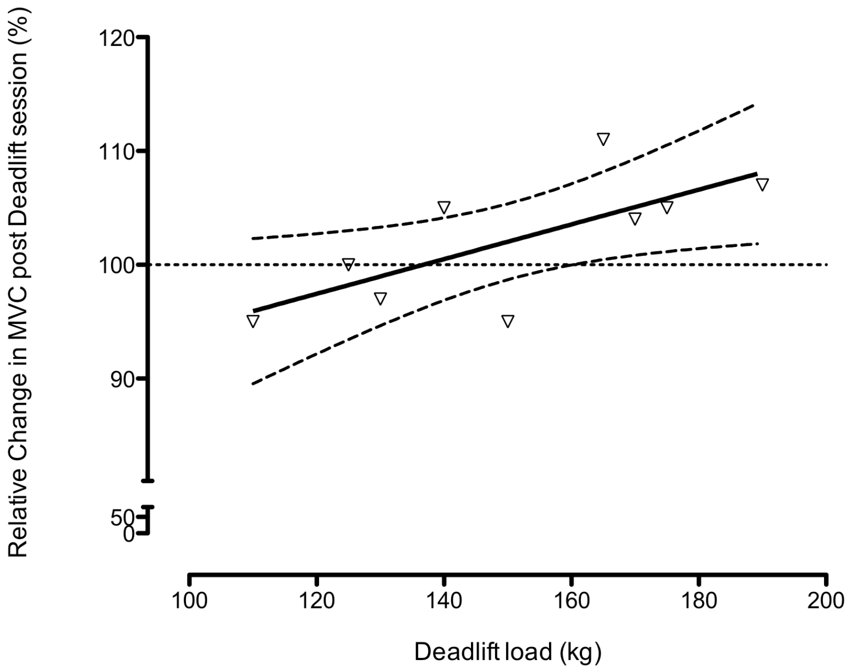

Figure A5. Relative MVC post deadlift session versus deadlift load lifted.
Significant relationship, where relative post MVC = 79.9 + 0.147 x deadlift load, $r^2 = 0.51$, $p<0.05$. The 90% confidence intervals are shown by the dotted line.

Discussion and practical application:

Subjects who lifted heavier loads were more likely to experience positive increases in MVC force, 10 minutes following five sets x five repetitions of deadlift. This finding agrees with previous research showing a positive relationship between strength and the realisation of post activation potentiation (Chiu *et al.*, 2003; Robbins, 2005). However, post-activation potentiation is not normally associated with increased peak force (Tillin & Bishop, 2009).

In addition, there were correlations found between the maximum knee angle and the normalised RMS amplitude during the deadlift exercise. This may explain the relationship between post session MVC and deadlift load. Subject who used higher loads, with possibly a different lifting technique, also had greater quadriceps muscle activation. Consequently, they benefitted from a superior stimulus leading to potentiation. This explanation may rely upon the assumption that the increased sEMG represented greater

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type II motor unit activation, which have greater potentiation potential (Chiu *et al.*, 2004; Hamada, Sale, MacDougall, *et al.*, 2000). The squat load was also correlated with subjects' RMS amplitude during squat performance, however there was no relationship between the post MVC and squat load, probably due to the increased fatigue masking any potentiation effects.

These findings also suggests that the better (or stronger) an individual is at performing a specific exercise, the more beneficial the exercise may be in terms of motor unit activation. Consequently, training effects may increase with absolute, as well as relative training level. This is an interesting concept for coaches and athletes, what may benefit from further investigation.

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Appendix 6: Case study: Neuromuscular response and 24-hour recovery following an explosive resistance exercise session alongside sprint training.

Aim:

To investigate if two strong elite sprinters would benefit from a positive neuromuscular response post- explosive resistance exercise following sprint running training.

Methods:

Two male elite sprint athletes (aged 24 & 29 years, body mass 79 & 89 kg) completed the following training following a rest day on the Sunday: Monday at 0900hrs, a standard personal warm up followed by a speed endurance session at 1030hrs (2x300m, 4x100m at 12-13 s/100m pace). At 1400, a warm up was followed by a resistance exercise session (seven sets x three repetitions of snatch and jump squats + five sets x four repetitions of step ups). MVC, CAR and Jump tests were performed following the warm ups prior to running, resistance exercise sessions and also following the resistance exercise session. Tests were repeated the following day (Tuesday) at 0900hrs. A summary of the tests is presented below. The results from both subjects are presented together as they followed the same pattern of response.

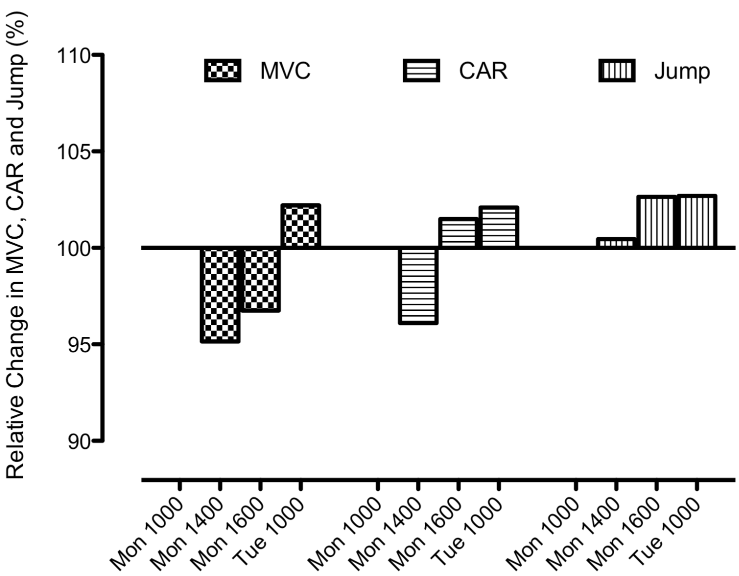

Figure A6. MVC, CAR and Jump for each time point relative to the Monday AM tests.

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Summary:

MVC and CAR decreased following running sessions, with Jump unchanged. All three tests increased following the Monday PM resistance exercise session, with CAR and Jump going above baseline. All three tests were above baseline on Tuesday AM. Together these findings suggest for these two elite-trained sprinters, who were fully accustomed to their training programme, increased neuromuscular function occurred following an explosive type session. In addition the post-session response was associated with a good 24-hour neuromuscular recovery.

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Appendix 7: Active Muscle RPE scale and descriptive anchors

6	no exertion at all
7	extremely light
8	
9	very light
10	
11	light
12	
13	somewhat hard
14	
15	hard (heavy)
16	
17	very hard (very heavy)
18	
19	extremely hard
20	maximal exertion

During this exercise session we are going to measure your perceptions of exertion in the muscles that you use to perform the squat, deadlift, etc. Focus on the thigh and hip muscles. Give a rating of your perceived exertion after the 5th repetition, specifically to the effort required for that repetition.

A rating of 20 is the hardest maximal lift you have ever performed. E.g. the last rep of a really tough set of squats you almost failed to lift.

A rating of 11 is similar to a warm up set using light weights at about 50%.

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