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Time Course of Changes in Neuromuscular Parameters during Fatiguing High-Load and Low-Load Concentric Dynamic Constant External Resistance Leg Extension Muscle Actions

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by

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The purpose of this study was to simultaneously assess electromyographic (EMG) and mechanomyographic (MMG) signals to examine the time course of changes in EMG amplitude, EMG frequency, MMG amplitude, and MMG frequency from the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) muscles during high-load (70%1 repetitions maximum; 1-RM) and low-load (30% 1-RM) concentric, dynamic constant external resistance (DCER) leg extension muscle actions to failure. Twelve men performed two randomized visits consisting of either 30 or 70% 1-RM DCER leg extension muscle actions to failure. Maximal voluntary isometric contractions (MVIC) and 1-RM measurements were performed before and after each protocol. Electromyographic amplitude, EMG frequency, MMG amplitude, and MMG frequency were measured from the VL, VM, and RF. The results indicated mode- (DCER versus isometric) and intensity-specific (30 versus 70% 1-RM) differences in the 1-RM and MVIC measurements. There were increases in EMG amplitude and MMG amplitude, but decreases in EMG frequency and MMG frequency during both the 30 and 70% 1-RM protocols. The time course of changes in neuromuscular responses, however, were unique to each protocol and muscle. The 30% 1-RM protocol had three unique phases (1 to 30, 30 to 60, and 60 to 100% of the repetitions to failure), but the 70% 1-RM protocol had

only one phase (1 to 100% of the repetitions to failure). These time course of changes in neuromuscular responses during both the 30 and 70% 1-RM protocols could be explained by Muscle Wisdom and the Onion Skin Scheme, but not the After-Hyperpolarization theory. The findings of the current study suggested that the time course of changes in neuromuscular responses can provide insight in muscle- and intensity- specific differences in the motor unit activation strategies used to maintain force production and allow for a greater understanding of the fatiguing process by identifying the time-points at which these neuromuscular parameters changed.

Dedication

I would like to dedicate this Thesis to those that have supported and mentored me throughout my many endeavors in life. Specifically, I would like to show my appreciation for my parents, Lori and Derek Smith, who have given me support and insight throughout my life. I would also like to thank my advisor, Dr. Housh, and the rest of my committee for the uncountable hours they have dedicated to help me develop my skills as an instructor and researcher. In addition, my fellow lab mates have been invaluable colleagues and friends throughout this process. In particular I would like to especially thank Ethan Hill for his support, friendship, and teamwork in the past years and years to come.

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Chapter I

Introduction

Surface electromyography (EMG) and mechanomyography (MMG) are non-invasive procedures that are used to examine neuromuscular function during isometric and dynamic muscle actions[1-8]. The amplitude of the EMG signal represents muscle activation and the frequency content is related to motor unit action potential conduction velocity (MUAP CV)[1]. The MMG signal, however, has been described as the mechanical counterpart of the motor unit electrical activity measured by EMG and quantifies the low-frequency lateral oscillations of activated skeletal muscle fibers[8-10]. Under certain conditions, the amplitude of the MMG signal reflects motor unit recruitment and the frequency content is a qualitative indicator of the global motor unit firing rates of unfused, activated motor units[9,10].

Simultaneous assessments of EMG and MMG have been used to examine factors associated with muscle function such as phonomechanical and electromechanical delay[11], EMG and MMG versus isometric and isokinetic torque relationships[2,12-14], skeletal muscle atrophy[15], and the neuromuscular effects of resistance training[4,7,16,17]. Clinically, EMG and MMG have been used in the assessment of neuromuscular disorders including cerebral palsy[18,19], myotonic dystrophy[20], cranio-mandibular disorders[21,22], and chronic and severe low back pain[23], as well as to control externally powered prostheses[24,25].

A primary application of the simultaneous measurements of EMG and MMG signals is to determine the dissociations between the electrical and mechanical events of excitation-contraction coupling that occur with fatigue[9,12,26-31]. Together, the time and frequency domain parameters of EMG and MMG signals can provide information regarding the contributions of muscle activation (EMG amplitude)[1], MUAP CV (EMG frequency)[1], motor unit recruitment (MMG amplitude)[9,10], and global motor unit firing rate (MMG frequency)[9] to the motor unit activation strategies that modulate force production during fatiguing tasks. Typically, fatiguing, submaximal isometric and isokinetic muscle actions, as well as cycle ergometry result in increases in EMG and MMG amplitude, but decreases in frequency contents of the EMG and MMG signals. Thus, submaximal, fatiguing tasks are usually characterized by increases in muscle activation and motor unit recruitment, but decreases in MUAP CV and global motor unit firing rate. Fatiguing, maximal isometric and concentric isokinetic muscle actions, however, have been shown to result in decreases in the amplitude and frequency content of both the EMG and MMG signals[12]. During fatiguing, maximal eccentric muscle actions there are increases in MMG amplitude, decreases in EMG and MMG frequency, and no change in EMG amplitude[32]. Thus, the patterns of the neuromuscular responses to fatigue can be influenced by factors such as the force and/or power output (% maximal) of the task as well as the mode of muscle action (isometric vs. concentric vs. eccentric muscle actions). Although previous studies have examined the EMG and MMG responses to fatiguing isometric and isokinetic (concentric and eccentric) muscle actions, no previous studies have simultaneously examined the fatigue-related patterns of responses for the time and frequency domain parameters of EMG and MMG signals during dynamic constant external resistant (DCER) muscle actions to failure.

Neuromuscular responses have often been examined using polynomial regression models to examine the patterns of fatigue-related responses or pretest vs. posttest assessments of EMG and MMG parameters to determine the overall magnitude of the effects of the fatiguing task. Since fatigue is a process that occurs throughout an exhaustive task, the time course of fatigue-related changes in neuromuscular parameters associated with motor unit activation strategies are dependent on which specific time or frequency domain parameter of the EMG or MMG signal is being assessed[9,33]. Thus, the time-dependent changes in the patterns of EMG and MMG time and frequency domain parameters may be valuable for identifying the changes in motor unit activation strategies used to meet the demands of various types of fatiguing tasks. Furthermore, the patterns of neuromuscular responses to fatigue are often muscle specific[4,16]. For example, Akima et al.[16] reported greater muscle activation from the VL compared to the VM and RF and differences in muscle activation during high-load (70% 1-repetition maximum, RM) and low-load (50% 1-RM) DCER leg extension muscle actions to failure. In addition, Jenkins et al.[7] reported different rates of change in MUAP CV from the VL, VM, and RF during both high-load (80% 1-RM) and low-load (30% 1-RM) DCER leg extension muscle actions to failure. Therefore, the purpose of this study was to simultaneously assess EMG and MMG signals to examine the time course of changes in EMG amplitude, EMG frequency, MMG amplitude, and MMG frequency from the VL, VM, and RF muscles during high-load (70%1-RM) and low-load (30% 1-RM) concentric, DCER leg extension muscle actions to failure. This study is unique from previous studies because it simultaneously examines the fatigue-related time course of changes in time and frequency domain parameters of both EMG and MMG signals from the three superficial muscles of the quadriceps femoris during repeated, submaximal, DCER muscle action of the leg extensors to failure at two different loads.

Based on the findings of Merletti et al.[33] it is hypothesized that in the present study there will be increases in EMG amplitude and MMG amplitude, and decreases in EMG frequency and MMG frequency during both the high-load and low-load DCER leg extension muscle actions to failure. In addition, Merletti et al.[33] suggested that the time course of changes in time and frequency domain parameters of the EMG signal and motor unit activation strategies are influenced by the intensity of the muscle action. Therefore, it is hypothesized that the time course of changes in the time and frequency domain parameters from the EMG and MMG signals will be different during the high-load and low-load DCER leg extension muscle actions to failure. Specifically, the high-load will result in a greater rate of increase in EMG amplitude and MMG amplitude compared to low-load DCER leg extension muscle actions to failure. In addition, the high-load will result in a decrease in EMG frequency and MMG frequency sooner than the low-load, however, there will be a greater decrease in EMG frequency and MMG frequency in the low-load compared to high-load DCER leg extension muscle actions.

Chapter II

Review of Literature

2.1 DCER and Isometric Mode Specific Fatigue Responses

Akima and Saito (2013)

The purpose of this investigation[16] was to examine the neuromuscular parameters of the four quadriceps femoris muscles from nine male subjects (mean ± SD = 24.7 ± 7.7 yrs) during dynamic constant external resistance (DCER) leg extensions with loads of 50 and 70% one repetition maximum (1-RM) performed until exhaustion. Electromyographic (EMG) amplitude was recorded and analyzed separately for both the concentric (CON) and eccentric (ECC) portions of the muscle actions and at three different phases of the range of motion (ROM)(90 to 115°, 115 to 140°, and 140 to 165°) for the vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), and vastus intermidius (VI). The results indicated that there were linear increases for the EMG amplitude for all muscles for both 50 and 70% 1-RM DCER leg extensions to exhaustion and during all phases of the range of motion. There were significant differences in EMG amplitude for the VM between 50 and 70% 1-RM protocols, however, there were no differences between the 50 and 70% 1-RM protocol for the VL, RF, and VI. The EMG amplitude from the VM was greatest when near full extension at 70% 1-RM compared to 50% 1-RM. All four muscles of the quadriceps femoris had greater EMG amplitude near full leg extension for both protocols. The authors[16] concluded that during fatiguing DCER muscle actions of the leg extensors, joint angle and intensity affect muscle activation and the patterns of responses of the neuromuscular activations patterns from the VL, VM, RF, and VI.

Masuda, Masuda, Sadoyama, et al. (1999)

The purpose of this investigation[34] was to examine the changes in neuromuscular time and frequency domain parameters of the vastus lateralis (VL) from 19 male subjects (range = 19 – 73 yrs) during a sustained isometric muscle action of the leg extensors at 50% maximal voluntary isometric contraction (MVIC) to failure. After 30-min of rest, dynamic constant external resistance (DCER) leg extensions to failure at 50% MVIC were performed. The results indicated that the sustained isometric muscle action of the leg extensors (mean = 75.7-s) was shorter in duration than the DCER leg extensions (mean = 149.7-s). Motor unit action potential conduction velocity (MUAP CV) during the sustained isometric muscle action increased from 0 to 15% of the time to exhaustion and then began to decrease at 20% of the time to exhaustion until failure. The MUAP CV, however, did not change during the DCER leg extension. The electromyographic (EMG) frequency began to decrease from the beginning of both the sustained isometric and DCER leg extensions, with the greatest rate of decline beginning at 60% of the time to exhaustion until failure. The EMG amplitude began to increase from the initiation of the muscle action until failure for both the sustained isometric and DCER leg extensions, however, DCER leg extensions resulted in greater EMG amplitude compared to the sustained isometric muscle actions throughout the time to exhaustion. The authors concluded that DCER muscle actions responded differently than sustained isometric muscle actions because of the stretch-shortening cycle that increases blood flow to the muscle and decreases the effects of metabolic byproducts.

Housh, Housh, and Weir (1996)

The purposes of this study[35] were to examine the effects of eight weeks of unilateral concentric (CON) only dynamic constant external resistance (DCER) leg extension training on trained and untrained limbs one repetition maximum (1-RM), isokinetic torque-velocity curve, as well as the effects of eight weeks of detraining. Sixteen male subjects (mean ± SD = 24 ± 4 yrs) performed eight weeks of CON only DCER leg extension training three days a week at 80% 1-RM. The trained and untrained limbs showed an increase in DCER 1-RM post training and after the 8-wks of detraining. The effect of DCER leg extension training on the trained limb increased the isokinetic torque-velocity curve post training and after detraining at velocities greater and less than the velocity of the DCER training. The isokinetic torque-velocity curve from the untrained limb changed after post training and detraining. The authors concluded that DCER leg extension training resulted in increases in 1-RM for both the trained and untrained limb, as well as increased isokinetic torque from only the trained limb post training and after eight weeks of detraining. This suggested that cross-training is mode specific and that 86 to 93% of the increases in 1-RM strength can be retained following eight weeks of detraining.

Hollander, Kraemer, Kilpatrick et al. (2007)

The purpose of this study[36] was to determine the differences in maximal concentric (CON) and eccentric (ECC) dynamic constant external resistance (DCER) strength in both men and women. On two separate testing sessions 10 men (mean ± SD = 25.3 ± 1.3 yrs) and 10 women (mean ± SD = 23.4 ± 1.4 yrs) performed CON only and ECC only DCER leg extension one repetition maximum (1-RM) testing. The results indicated that men have greater 1-RM values than women, but women have a greater ECC to CON ratio (1.57) than men (1.38). In addition, the men's average CON 1-RM was 25% less than the ECC 1-RM and females CON 1-RM was 39% less than the ECC 1-RM. The authors concluded that there were differences between men and women for both CON and ECC 1-RM, ECC/CON ratios, and suggested that men and women training programs be analyzed separately to account for gender differences.

Weir, Housh, Evens et al. (1993)

The purpose of this study[37] was to examine the effects of dynamic constant external resistance (DCER) squat and leg extension training on isokinetic peak torque and constant joint angle torque-velocity curves from 0 to 5.03 $rad \cdot s^{-1}$. Twelve men (mean ± SD = 21.7 ± 2.6 yrs) performed eight weeks of DCER squat and leg extension training three days a week (three sets x six repetitions at 6-RM). The results indicated increased squat (27%) and leg extension (36%) 6-RM strength, as well as increases in joint angle torque-velocity curves (6.3 to 10.7%) and isokinetic peak torque (8.1 to 10.9%) The authors concluded that DCER squat and leg extension training resulted in increased 6-RM strength that transferred to increases in isokinetic leg extension peak torque and increased torque production at all constant joint angle torque-velocity curves.

Weir, Housh, Housh et al. (1997)

The purposes of this investigation[38] were to examine the effects of concentric (CON) only dynamic constant external resistance (DCER) leg extension training and detraining on joint angle specificity, cross-training, and the bilateral deficit. Sixteen male subjects were separated into a control group (n = 8, mean ± SD = 24.1 ± 5.0 yrs) or training group (n = 8, mean ± SD = 23.9 ± 3.9 yrs). The training group performed unilateral CON only DCER leg extension training three days a week (five sets x six repetitions at 80% one repetition maximum (1-RM)), for eight weeks. A maximal voluntary isometric contraction (MVIC) and DCER 1-RM were measured pre training, post training, and after eight weeks of detraining from the trained limb, untrained limb, and bilateral leg extensor muscles. The results indicated that DCER strength training increased MVIC torque at all joint angles for each limb post training (13%), but not after detraining. In addition, DCER leg extension training increased the trained limb (29%), untrained limb (13%), and bilateral limbs (22%) 1-RM post training, and maintained these increases after detraining. There was not a bilateral deficit pre training, however, post training and after detraining there was a bilateral deficit for the trained limb. The authors concluded that DCER leg extension training is effective at increasing isometric strength at all joint angles. In addition, cross-training and bilateral deficit occurred as a result of unilateral CON only DCER leg extension training.

<u>Jenkins, Housh, Bergstrom et al. (2015)</u>

The purposes of this study[7] were to identify the changes in electromyographic (EMG) amplitude, EMG frequency, exercise volume, muscle activation, time under concentric (CON) load, and muscle cross-sectional area (CSA) during dynamic constant external resistance (DCER) leg extensions at 80% and 30% one repetition maximum (1-RM) for three sets to failure. Bi-polar electrode arrangements were placed over the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) of nine trained men (mean ± SD = 21.0 ± 2.4 yrs) and nine trained women (mean ± SD = 22.8 ± 3.8 yrs) during three sets of DCER leg extensions to failure at 80% and 30% 1-RM on two separate testing sessions. In addition, ultrasound was used to obtain the CSA immediately before and after each testing session. The results indicated that the volume of work performed at each set during 30% 1-RM (set one = 2000 kg, set two = 1150 kg, set three = 900 kg) was greater than 80% 1-RM (set one = 1100 kg, set two = 800 kg, set three = 750). The total EMG amplitude from the composite of all muscles for 80% 1-RM was greater than 30% 1-RM for each set. In addition, EMG amplitude from 80% 1-RM increased within sets, but did not change between sets. The EMG amplitude from 30% 1-RM increased within sets, and EMG amplitude during set 3 increased (15%) from set 1 and set 2. The EMG frequency during the 80% 1-RM for each set began to decrease from the initial repetition and continued until failure, however, during 30% 1-RM EMG frequency did not begin to decrease until 50% of the repetitions to failure. In addition, EMG frequency from 30% 1-RM decreased greater than 80% 1-RM. Cross-sectional area following 30% 1-RM were greater than 80% 1-RM for the VL and RF. The authors concluded that muscle activation was lower for 30% 1-RM than 80% 1-RM. Also, greater EMG frequency decreases occurred during 30% 1-RM compared to 80% 1-RM despite fatigue-induced increases in EMG amplitude for both 30% and 80% 1-RM. These findings suggested that both 30% 1-RM and 80% 1-RM may induce hypertrophy, however, greater increases in strength will likely result from training at 80% 1-RM.

Pincivero, Gandhi, Timmons et al. (2006)

The purpose of this study[39] was to examine the differences between genders electromyographic (EMG) responses during dynamic constant external resistance (DCER) leg extensions at 50% one repetition maximum (1-RM) until failure. Bipolar EMG electrodes were placed over the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) of 15 men (mean ± SD = 25.7 ± 3.9 yrs) and 15 women (mean ± SD

= 22.4 ± 2.4 yrs) to identify the EMG amplitude and EMG frequency responses to a single set of DCER leg extensions to failure at 50% 1-RM. The results indicated that EMG amplitude from the VM and VL were greater for the women compared to the men. The EMG amplitude increased from the VL (25%), VM (15%), and RF (20%), and EMG frequency decreased from the VL (25%), VM (20%), and RF (30%) during the concentric (CON) phase of the DCER leg extensions to failure. The authors concluded that during the CON phase of the DCER leg extensions there was a buildup of metabolic byproducts that reflected a decrease in EMG frequency, and the muscle activation increased throughout the DCER leg extensions, however, there was a gradual decline in quadriceps femoris muscle recruitment near the end of the DCER leg extensions. These findings suggested a difference between men and women's responses to DCER leg extensions. In addition, these findings suggested that DCER leg extensions to fatigue resulted in an increase in the buildup of metabolic byproducts and an increase in muscle activation.

Pincivero, Coelho, Campy (2008)

The purpose of this study[40] was to examine the gender differences in electromyographic (EMG) amplitude and EMG frequency during dynamic constant external resistance (DCER) leg extensions at varying percent's of one repetition maximum (1-RM). Fifteen men (mean ± SD = 25.1 ± 4.0 yrs) and 15 women (mean ± SD = 22.9 ± 3.2 yrs) performed two repetitions every 10% of their 1-RM in a randomized order between 20 – 90% 1-RM. The results indicated that as the percent of the 1-RM increased, velocity decreased for both men and women. Men had greater velocities than women during the concentric (CON) phase, however, there were no differences in velocity during the eccentric (ECC) phase. The EMG amplitude from the vastus lateralis

(VL) was greater for men compared to women during the DCER leg extensions, however, the EMG amplitude from the rectus femoris (RF) was lower for men compared to women. The EMG frequency was greater for men compared to women for all measurements. The authors concluded that EMG signals recorded during DCER muscle actions differ between genders, and suggested that DCER leg extensions relied heavily upon the VL for both genders. These findings suggested that EMG signals recorded from men and women during DCER muscle actions should be analyzed separately.

Remaud, Cornu, Guevel (2010)

The purpose of this study[41] was to identify the differences in neuromuscular adaptations between isotonic and isokinetic strength training. Thirty men (mean ± SD = 20.7 ± 2.3 yrs) were equally separated into a control group, isokinetic training group, and isotonic training group. The isokinetic training group performed concentric (CON) only isokinetic training, five sets x eight repetitions three days a week, at 40% peak torque for eight weeks. The isotonic training group performed CON only isotonic training, five sets x eight repetitions 3 days a week, at 40% 1-RM for eight weeks. Pretest and posttest maximal voluntary isometric contractions (MVIC) were performed for all groups. In addition, bipolar electromyographic (EMG) electrodes were placed over the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) for all pretest and posttest measurements to identify the neuromuscular adaptations associated with isokinetic and isotonic strength training. The results indicated that there were increases in isotonic one repetition maximum (1-RM) for both the isokinetic (16.1%) and isotonic (13.3%) training groups, but not for the control group. Isokinetic peak torque also increased at all velocities for both the isokinetic and isotonic training group, but not for the control group. In addition, MVIC torque values increased for the isokinetic (13.3%) and isotonic (7.6%) training groups, as well as increases in muscle activity (EMG amplitude) for both the isokinetic (31.7%) and isotonic (33.5%) training groups. The total muscle activity (EMG amplitude) during isotonic 1-RM increased for the isokinetic (11.6%) and isotonic (12.9%) training groups compared to pretest measurements. The total muscle activity (EMG amplitude) during isokinetic peak torque measurements increased for the isokinetic (21.9%) and isotonic (28.8%) training groups compared to pretest measurements. The authors concluded that isokinetic and isotonic training increased muscle activation (EMG amplitude), which resulted in increased strength during static and dynamic muscle actions. In addition, eight weeks of dynamic CON only strength training increased strength at all velocities and modes of exercise (isokinetic and isotonic). These findings suggested that increases in muscle activity (EMG amplitude) and strength following dynamic CON only training is not dependent on the velocity or mode of exercise being performed.

<u>Walker, Davis, Avela et al. (2012)</u>

The purpose of this study[42] was to examine the changes in neuromuscular parameters following maximal strength and hypertrophic dynamic constant external resistance (DCER) leg press exercise. Thirteen men (mean ± SD = 28.4 ± 3.7 yrs) performed a maximal strength (10 sets x one repetition at 100% one repetition maximum (1-RM)) and hypertrophic (five sets x 10 repetitions at 80% 1-RM) protocol while electromyographic (EMG) measurements were taken from the vastus lateralis (VL) and vastus medialis (VM). In addition, blood lactate samples were obtained from fingertip samples during both protocols. Pretest, posttest, and 15-min posttest maximal voluntary isometric contraction (MVIC) measurements were measured during either protocol. The EMG amplitude from the maximal strength protocol increased from set one to set three, and then began to decrease from set three to set 15. The EMG amplitude from the hypertrophic protocol increased from set two to set five. The posttest MVIC torque values were lower than MVIC torque values, and 15-min posttest MVIC torque values were greater then posttest values but did not return to pretest values for both protocols. Blood lactate levels increased for both protocol, however, the hypertrophic protocol lactate levels were greater than maximal strength protocol. The authors concluded that the muscle activation strategies are load dependent and that maximal strength training fatigue was a result of neural drive to the muscle and hypertrophic training is a result of peripheral fatigue.

2.2 Time and Frequency Domain Parameters

<u>Roy, De Luca, Schneider (1986)</u>

The purpose of this study[43] was to examine the effects of electrode location on the motor unit action potential conduction velocity (MUAP CV) and median frequency estimates from the electromyographic (EMG) signal obtained from 10 men (range = 23 – 40) during three isometric muscle actions of the anterior tibialis at 20% and 80% maximal voluntary isometric contraction (MVIC). The results of the study indicated that median frequency values were similar to the MUAP CV. In addition, electrode locations located over the innervation zone (IZ) and tendinous regions of the muscle resulted in greater frequency values compared to electrode locations recorded away from the IZ or tendinous regions. The authors concluded that electrode placements should avoid the IZ and tendinous region of the muscle because they result in increased frequency measurements. It was also concluded that median frequency measurements closely reflected MUAP CV and therefore are an indicator of MUAP CV when a linear array of electrodes are not available.

Arendt-Nielsen and Mills (1988)

The purpose of this study[44] was to examine the effects of submaximal fatiguing muscle actions above 60% maximal voluntary isometric contraction (MVIC) on motor unit action potential conduction velocity (MUAP CV), electromyographic (EMG) frequency, and force production. Five men (range = 22 – 39 yrs) performed sustained isometric muscle actions of the leg extensors to failure every 10% from 60% to 100% MVIC while recording EMG signals were taken from the vastus lateralis (VL). The results indicated that MUAP CV and EMG frequency decreased during all sustained isometric muscle actions from 60% to 100% MVIC, however, the greater the % MVIC the greater the decreases in MUAP CV. The EMG frequency decreased greater at 60, 70, and 80% MVIC compared to 90% and 100% MVIC. This was likely a result of greater time to failure from the 60, 70, and 80% MVIC compared to 90, 100% MVIC sustained isometric muscle actions. Electromyographic amplitude increased during all the sustained isometric muscle actions from 60 to 100% MVIC, and the greater the % MVIC the greater the rate of increase in EMG amplitude. In addition, the greater the % MVIC performed during sustained isometric muscle actions, the greater the decline in maximal force production that occurs. The authors concluded that EMG frequency represents MUAP CV. In addition, fatiguing muscle actions at and above 60% MVIC resulted in decreases in MUAP CV and EMG frequency as a result of the buildup of metabolic byproducts as well as the recruitment of less fatigued motor units with faster MUAP CV.

The EMG amplitude tracks force production and increases during fatiguing tasks until force begins to decline. The results indicated that during the intermittent isometric muscle actions at low weights there were no changes in mechanomyographic (MMG) amplitude. In addition, as the weight increased so did MMG amplitude, and as the weight decreased MMG amplitude decreased for both the intermittent and sustained isometric muscle actions. The authors concluded that MMG amplitude reflects increases in muscle activation and is associated with increases in force.

Barry, Geiringer, and Ball (1985)

The purpose of this study[45] was to examine the mechanomyographic (MMG) amplitude from the biceps brachii during sustained and intermittent isometric muscle actions. During the intermittent isometric muscle actions five subjects held weights (zero, five, 10, 12.5, 15, and 20 lbs) out with the elbow bent at a 90° angle for 20-s followed by 10-s of rest between each weight. Ten subjects performed a sustained isometric muscle action of the biceps brachii that required each subject to begin at 75% maximal voluntary isometric contraction (MVIC) and continue until subjects could no longer maintain 35% MVIC. The results indicated an increase in MMG amplitude with an increase in force. When force decreased as a result of fatigue, MMG amplitude did not decrease substantially, however, when force was decreased voluntarily MMG amplitude decreased. The authors concluded that MMG amplitude reflects muscle activity and is a direct indicator of muscular contraction. In addition, it was suggested that analyzing EMG signals concurrently with MMG signals allows for a greater identification of motor unit activation strategies.

Dimitrov, Arabadziev, Mileva et al. (2006)

The purpose of this study[46] was to examine the effectiveness of new electromyographic (EMG) spectral indices designed for assessing peripheral muscle fatigue during dynamic leg extensions. The EMG signal from the rectus femoris (RF) was collected from seven subjects (mean ± SD = 28.7 ± 7.0 yrs) that performed dynamic constant external resistance (DCER) leg extensions, three sets x 15 repetitions, at 50% one repetition maximum (1-RM) with a pretest and posttest MVICs. The concentric (CON) and eccentric (ECC) phases of the DCER leg extensions were analyzed separately. The new EMG spectral indices method for detecting muscle fatigue during dynamic muscle actions identifies the ratio of change between the spectral moments. The results indicated that the new EMG spectral indices were more sensitive to changes in the CON and ECC phases across repetitions than mean power frequency or median power frequency when analyzing fatiguing dynamic muscle actions of the leg extensors. Therefore, the authors concluded that the new spectral indices identify the changes in EMG frequency more accurately than mean power frequency alone.

Gonzalez-Izal, Malanda, Navarro-Amezqueta et al. (2010)

The purpose of this study[47] was to examine the sensitivity of surface electromyographic (EMG) indices using discrete and stationary wavelet transform to estimate fatigue induced changes of the EMG signal during dynamic muscle actions. Fifteen men (mean ± SD = 34.2 ± 5.2 yrs) performed five sets x 10 repetitions of concentric (CON) only dynamic leg press at 10 repetition maximum (10-RM). The EMG signals were recorded from the vastus medialis (VM) and were processed through stationary wavelet transform (SWT) and discrete wavelet transform (DWT). The SWT and DWT both showed increases in EMG amplitude, and decreases in EMG frequency, however, the SWT was more sensitive to changes in frequency during fatiguing, high-powered, dynamic muscle actions. The authors concluded that when performing wavelet based EMG signal analyses the SWT method was more sensitive during dynamic muscle actions and can detect subtle changes in frequency even with the Gaussian noise and signal cancellation associated with bipolar surface EMG.

<u>Fortune and Lowery (2007)</u>

The purpose of this study[48] was to examine the effects of extracellular potassium (K^+) concentration on motor unit action potential conduction velocity (MUAP CV) using a simulated model. The model was developed in Matlab, and consisted of increased extracellular K^+ by simulating fatigue induced changes in the surface membrane capacitance, temperature, tubular lumen conductance, fiber radius, length of fiber segment, tubular membrane capacitance, and time intervals. Extracellular K^+ was simulated at five, six, seven, eight, nine, and 10 mM. The results indicated that as extracellular K^+ increased, MUAP CV decreased. In addition, at lower temperatures the MUAP CV was slower than at higher temperatures for all simulated K^+ levels. The resting membrane potential also increased with increased extracellular K^+. The authors concluded that increased extracellular K^+ results in decreased amplitude, reduction in MUAP CV, and broadening of the action potential.

<u>Kuiken, Lowery, Stoykov (2003)</u>

The purpose of this study[49] was to examine the effects of subcutaneous fat on the surface electromyographic (EMG) signal and cross-talk of nearby muscle. A model made from skin, fat, muscle, and bone from a human arm was used to measure the effects of different subcutaneous fat layers on the EMG signal obtained from bipolar electrodes.

The motor unit action potentials (MUAP) were simulated and continuously transmitted through 500 single muscle fibers in the arm model. Four different fat thicknesses were measured (zero mm, three mm, nine mm, and 18mm) and electrodes were placed around the circumference of the model every 7.5°. The results indicated that as the fat thickness increased, EMG amplitude decreased (up to 241%) and the amount of cross-talk increased (up to 68%). The authors concluded that subcutaneous fat decreased EMG amplitude and increased cross-talk from nearby muscles, therefore, it may be beneficial to measure subjects with less subcutaneous fat or select locations that have less subcutaneous fat.

2.3 EMG and MMG Patterns of Responses and Motor Unit Activation Strategies during Fatiguing Muscle Actions

<u>Tarata (2003)</u>

The purpose of this study[29] was to identify the differences between mechanomyography (MMG) and electromyography (EMG) in monitoring fatigue during a sustained isometric muscle action to failure of the biceps brachii and brachialis at 25% MVIC from 18 participants (range = 23 – 35 yrs). The results indicated that during a fatiguing muscle action EMG and MMG amplitude increases, and EMG and MMG frequency decreases. The MMG frequency decreased similarly to the decrease of EMG frequency, but, MMG frequency values were lower than EMG MPF. The EMG amplitude and MMG amplitude values tracked each other throughout the fatiguing muscle action, however, MMG amplitude plateaued during the last five percent of the time to failure. The authors concluded that both EMG and MMG provide insight into central and peripheral fatigue factors. In addition, the MMG signal, in conjunction with the EMG signal, can be used to identify the amount of muscle activation and development of fatigue throughout a fatiguing muscle action.

Beck, Stock, and DeFreitas (2014)

The purpose of this study[50] was to examine the changes in electromyographic (EMG) spectral shape from the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) of 12 men (mean ± SD = 22.2 ± 1.3 yrs) during 50 concentric (CON) only fatiguing muscle actions on an isokinetic dynamometer at $180°s^{-1}$. The results indicated a decrease in EMG mean power frequency from the VL, VM, and RF following the fatiguing muscle actions. When the EMG frequency was analyzed using the wavelet analyses there were decreases in the high-frequency band, and an increase in the low-frequency band of the power spectrum. In addition, during dynamic fatiguing muscle actions of the leg extensors the RF fatigued quickest, followed by the VL then the VM. These findings suggested that during dynamic fatiguing muscle actions there is a shift to the low-frequency end of the power spectrum and resulted in a decrease in EMG mean power frequency.

Dalton, Hons, and Stokes (1993)

The purpose of this study[51] was to examine the effects of fatiguing isometric muscle actions of the leg extensors and non-fatiguing dynamic muscle actions of the forearm flexors. The mechanomyographic (MMG) microphones were located over the rectus femoris (RF) (n = six) or biceps brachii (n = seven) (range = 17 – 32 yrs). The fatiguing isometric muscle actions of the leg extensors began at 75% maximal voluntary isometric contraction (MVIC) and continued until the subjects could no longer maintain

40% MVIC. Each muscle action was performed for 10 seconds followed by 10 seconds of rest. The subjects in the forearm flexion protocol performed a concentric (CON) and eccentric (ECC) dynamic muscle action of the forearm flexors using weights between zero to 8.5 kg. A three second isometric hold was performed between each CON and ECC muscle action. The results indicated an increase in MMG frequency with an increase in intensity during the isometric muscle actions of the leg extensors. The MMG frequency during the dynamic muscle actions increased from zero to 5.5kg, and then decreased from 5.5 to 8.5kg. The MMG frequency did not increase during the ECC phase, but did increase during the CON phase. The authors concluded that the MMG frequency may reflect motor unit activation strategies during isometric and dynamic muscle actions. It was also suggested that factors such as muscular stiffness, tremors, and muscle temperature may affect the MMG signal. In conclusion, the MMG frequency is capable of detecting changes in motor unit firing rate and the number of activated motor units during isometric and dynamic muscle actions.

<u>Akataki, Mita, Watakabe et al. (2001)</u>

The purpose of this study[52] was to examine the effects of aging on muscle activation and motor unit recruitment from the biceps brachii using mechanomyography (MMG) during isometric ramp muscle actions. Ten elderly men (range = 66 – 79 yrs) and 15 young men (range = 21 – 26) performed a ramp protocol beginning at 10% maximal isometric muscle contraction (MVIC) and continued up to 80% MVIC. The results indicated greater MMG amplitude and MMG frequency in the young men compared to the elderly men. The young men also had greater force production than the elderly men. The authors concluded that the MMG force relationship is able to detect changes in motor unit activation strategies in both the young and older populations. During two isometric ramp muscle actions there were increases in MMG amplitude and MMG frequency, which represent increased muscle activation and motor unit recruitment, respectively. In addition, there was a greater amount of slow-twitch motor units and fewer fast-twitch motor units in the elderly men compared to young men. These findings suggested that fatiguing studies measuring MMG should compare the elderly and young separately to allow for valid comparisons of the MMG responses.

Solomonow, Baratta, Shoji et al. (1990)

The purpose of this study[3] was to examine the effects of motor unit activation strategies and force generation rate on the electromyographic (EMG) force relationship of the gastrocnemius muscle of six cats during isometric muscle actions by stimulating the sciatic nerve. The sciatic nerve was stimulated with different discharge rates and voltages to identify 100, 90, 80, 70, 60, and 50% of motor unit recruitment and maximum force. The results indicated that all motor units become activated before maximal force is obtained, and that increases in discharge rates are responsible for the increased force following the activation of all motor units. In addition, during submaximal contractions there was a concurrent increase in motor unit activation and firing rate to achieve the required force. The authors concluded that the EMG-force relationship depends on the motor unit recruitment and discharge rate strategies. In addition, the normalized EMG values suggested that when the muscle is fatigued, force decreases at a slower rate than the motor unit discharge rate. Therefore, it is suggested that the EMG signal should not be used to predict force. The EMG signal, however, can be a useful tool to identify what motor unit activation strategies are modulating force during a fatiguing contraction.

Farina, Fosci, and Merletti (2002)

The purpose of this study[53] was to examine the sensitivity of the electromyography (EMG) frequency signals ability to identify motor unit recruitment strategies. A simulated model was used that stimulated synthetic motor unit action potentials (MUAP), muscle, fat, and skin during simulated sustained isometric muscle actions. The density and distribution was uniformly disturbed between 50 and 450 motor units. In addition, 10 men (mean ± SD = 26.3 ± 4.3 yrs) performed three ramp isometric muscle actions at torque values between zero to 80% maximal voluntary isometric contraction (MVIC) separated by two minutes of rest, followed by a sustained isometric muscle action at 80% MVIC for 11 seconds. The results indicated EMG frequency and MUAP conduction velocity (CV) were highly correlated, however, in the simulated experiment it was suggested that unstable motor unit pools may affect the correlation between EMG frequency and MUAP CV. In addition, during the fatiguing muscle actions from the simulation and composite of all subjects, EMG frequency and MUAP CV decreased at similar rates. During the ramp protocol, however, EMG frequency and MUAP CV increased with the increase in force requirement. The authors concluded that in unfatigued muscle the EMG frequency and MUAP CV increased with increases in force. During the sustained muscle actions, however, EMG frequency and MUAP CV decreased. These findings suggested that EMG frequency does not track the changes in torque, and therefore, EMG frequency alone may lead to inaccurate interpretations of the motor unit activation strategies used to modulate torque production during fatiguing and non-fatiguing isometric muscle actions.

Smith, Housh, Herda et al. (2015)

The purpose of this study was to identify the time course of changes in the electromyographic (EMG) and meachnomyogrpahic (MMG) signals during a sustained isometric muscle action of the leg extensors. Eleven subjects (mean ± SD = 22.5 ± 2.1 yrs) performed a sustained isometric muscle action of the leg extensors at 50% maximal voluntary isometric contraction (MVIC) to failure while EMG and MMG signals were measured from the vastus lateralis (VL). The results indicated that muscle activation (EMG amplitude) began to increase from the initiation of the muscle action and continued to increase until failure. Motor unit action potential conduction velocity (MUAP CV), EMG frequency, and global motor unit firing rate, MMG frequency, began to decrease at 30% of the time to exhaustion. Motor unit activation (MMG amplitude) increased from 10 – 30% of the time to exhaustion, and then decreased from 40-70% of the time to exhaustion, and then markedly increased from 70% of the time to exhaustion to failure. The authors concluded that motor unit activation strategies changed at about 30% and 70% of the time to exhaustion during a sustained isometric muscle action.

Jenkins, Housh, Buckner et al. (2015)

The purpose of this study[17] was to examine the changes in electromyographic (EMG) amplitude from the biceps brachii of 15 men (mean ± SD = 21.7 ± 2.47 yrs) during three sets to failure of dynamic constant external resistance (DCER) forearm flexion at a high-load (80% one repetition maximum (1-RM)) and low-load (30% 1-RM). The results indicated that the low-load group performed a greater number of repetition and volume compared to the high-load group. The results also indicated that EMG amplitude was greater in the high-load compared to the low-load group. The EMG amplitude increased at a greater rate during the low-load compared the high-load group.

The authors concluded that EMG amplitude increased during low-loads at a greater rate than high-loads, and that volume was lower during the high-load group compared to the low-load group. In addition, the authors suggested that the EMG responses may be dependent on the mode of exercise being performed and muscle being measured and suggested that future research examine the motor unit activation strategies during DCER leg extensions.

Rainoldi, Falla, Mellor et al. (2008)

The purpose of this study[54] was to examine the ability of the EMG signal to detect the differences in myoelectric manifestations of muscle fatigue between the vastus lateralis (VL) and vastus medialis (VM). Nine subjects (mean ± SD = 31.3 ± 8.6) performed isometric leg extensions at 60% and 80% maximal voluntary isometric contraction (MVIC) for 10 second and 60 second, respectively. The results indicated that EMG frequency from the VL and VM were greater during the 80% MVIC muscle action than the 60%MVIC muscle action. The EMG frequency recorded from the VL was greater compared to the VM. The EMG amplitude recorded from the VL and VM were greater during the 80% MVIC muscle action compared to the 60% MVIC muscle action. The EMG amplitude from the VL was greater compared to the VM. The VL had a greater overall decrease in EMG frequency than the VM. The authors concluded that the muscles of the quadriceps have different motor unit activation strategies and the EMG signal is a useful tool for identifying the time course of changes during sustained isometric muscle actions.

2.4 Mechanisms of Fatigue

<u>Bouissou, Estrade, Goubel et al. (1989)</u>

The purpose of this study[55] was to examine the effects of varying intramuscular pH on the electromyographic (EMG) power spectrum from the vastus lateralis (VL) of eight men (mean ± SD = 23.7 ± 4.0) during an exhaustive cycle ergometer ride at a power output of 375 watts. The subjects were randomized into a placebo or alkalosis group, and muscle biopsies were taken before and after the exhaustive ride. The results indicated that after the exhaustive exercise blood pH and blood lactate concentrations were greater in the alkalosis group compared to the placebo group. There was no difference in muscle pH between groups, however, the alkalosis group had greater muscle lactate compared to the placebo group. In addition, there was a decrease in EMG frequency and an increase in EMG amplitude during the exhaustive exercise for both the placebo and alkalosis group. The rate of decline in EMG frequency was greater in the alkalosis group compared to the placebo group. The authors concluded that the decrease in EMG frequency resulted from the buildup of metabolic byproducts. The authors also suggested a disassociation between intramuscular pH and EMG frequency, however, the methods used to detect changes may not have been sensitive enough to detect shifts towards the low-frequency band of the power spectrum.

<u>Cady, Jones, Lynn et al. (1989)</u>

The purpose of this study[56] was to examine the relationship between intracellular phosphorus metabolites, hydrogen ions, and force during fatiguing muscle actions. Four subjects (range = 21 – 43 yrs) performed two different fatiguing isometric muscle action of the first dorsal interosseous muscle. The fatiguing protocols required the subjects to perform three consecutive, 15 second maximal voluntary isometric contractions (MVIC).

Blood flow was occluded by an inflatable cuff placed around the upper arm at the onset of the first contraction in the first protocol, and then occluded blood flow for three minutes prior to performing the MVICs. Pretest and posttest measurements of P_i, PCr, ATP, H^+, pH, and ADP were performed on all subjects to measure the changes in metabolites. The results indicated a greater decrease in force the longer the muscle was in an ischemic state, however, force began to recover once blood flow was returned to the muscle. There was no relationship between ATP and force production. P_i increased throughout both fatiguing tasks, but increased the longer blood flow occlusion occurred. The pH of unfatigued muscle was 7.0, but decreased to 6.5 following the fatiguing MVICs. The accumulation of intracellular H^+ resulted in decreases in force. The ADP and ATP were not sensitive enough to draw conclusion between the changes in ADP and ATP levels and fatigue during brief MVIC muscle actions, however, PCr decreased as the muscle became more fatigued. The authors concluded that the buildup of metabolic byproducts (P_i and H^+) caused a greater decrease in force production than changes in energy stores (ATP, ADP, and PCr). These findings suggested that the buildup of metabolic byproducts results in fatigue by slowing motor unit action potential conduction velocity, decreasing cross-bridge recharging, and disrupting the excitation-contraction coupling.

Clausen (2013)

The purpose of this study[57] was to examine the effects of potassium (K^+) and sodium (Na^+) on membrane excitability and muscular fatigue. Potassium and Na^+ were measured from rat extensor digitorum longus muscles before and after a 60 second sustained stimulation at 60 Hz and 300 second sustained stimulation at five Hz. The results indicated a net decrease of K^+, but an increase in extracellular K^+ and Na^+ following both sustained stimulations, however, following 600 seconds of rest both the K^+ and Na^+ returned to baseline. In addition, the decreased K^+ resulted in the impaired uptake of Cl, which effected the detection of depolarization during longer lasting contractions, causing a slowing of motor unit action potentials (MUAP). These findings suggested that during fatiguing muscle actions there is a down-regulation of the Na^+K^+ pumps functional capacity that causes a greater buildup of metabolic byproducts, slowing down membrane excitability. The authors concluded that the buildup of extracellular K^+ following a fatiguing muscle action resulted in muscular fatigue by slowing membrane excitability.

<u>Juel (1988)</u>

The purpose of this study[58] was to examine the changes in electromyographic (EMG) signal, pH, extracellular potassium (K^+), and sodium (Na^+) gradient of mouse soleus and extensor digitorum longus muscles following electrical stimulated contractions. The results indicated that motor unit action potential conduction velocity (MUAP CV) measured from the EMG signal decreased over time. The decrease in MUAP CV was attributed to an increase in extracellular K^+, a decrease in intracellular pH, but extracellular pH and the Na^+ gradient did not affect MUAP CV. The authors concluded that MUAP CV is affected by extracellular K^+ and intracellular pH, and that the EMG signal can detect changes in MUAP CV.

<u>Lindstrom, Magnusson, and Peterson (1970)</u>

The purpose of this study[59] was to examine the changes in electromyographic (EMG) frequency and motor unit action potential conduction velocity (MUAP CV) from the biceps brachii from six men (range = 24 – 30 yrs) during a fatiguing (two kg isometric muscle action for 20 seconds, followed by a maximal contraction for 30 seconds, then another two kg isometric muscle action for 20 seconds). The results indicated that during a fatiguing muscle action MUAP CV decreases, and the power spectrum shifts towards the low-frequency band. A greater decrease in EMG frequency occurs as the muscle becomes more fatigued and indicates slowing of the MUAP CV. The authors concluded that during fatiguing muscle actions, EMG frequency and MUAP CV decreased as a result of decreased membrane excitability.

Bigland-Ritchie, Johansson, Lippold et al. (1983)

The purpose of this study[60] was to examine the relationship between contractile speed and the electromyographic (EMG) signals during a 60 second sustained maximal voluntary isometric contraction (MVIC) of the adductor pollicis muscle from eight subjects (range = 25 – 55 yrs). The 60 second sustained MVIC was performed three times. The first sustained MVIC was uninterrupted, the second sustained MVIC were briefly interrupted every 10 seconds to measure relaxation rates of the muscle, and the third was uninterrupted. An inflatable cuff was used to occlude the blood flow during the relaxation phase of the second isometric muscle action to allow the measurement of relaxation time from the muscle while under ischemic conditions. The results indicated that with practice, subjects could maximally activate all available muscle fibers (EMG amplitude). During the sustained MVIC there were decreases in force and contractile rate, however, there were no decreases in EMG amplitude once all available muscle was activated. The EMG frequency decreased during the sustained MVIC, but after 10 minutes of rest EMG frequency returned to pretest values. In addition, there were 50 –

70% decreases in MUAP CV, which was greater than the loss of force (30 – 50%). The authors concluded that maximal muscle activation can be obtained voluntarily, and the EMG amplitude increases during a fatiguing muscle action and can stay maximally activated even during a decrease in maximal force. In addition, during a sustained MVIC there was a progressive slowing of contraction speed, suggesting that the excitation rate required for maximal force production is reduced. Thus, decreases in EMG frequency may not be related to a loss of force production.

Chapter III

Methods

3.1 Subjects

Twelve men (mean ± SD age 21.9 ± 2.4 yr; body mass 76.7 ± 9.3 kg; height 175.8 ± 4.3 cm) volunteered to participate in this study. The subjects ranged between 19 to 26 years of age and were free from any musculoskeletal injuries or neuromuscular disorders, and performed resistance training for at least six months prior to the study. This study was approved by the University of Nebraska – Lincoln Institutional Review Board, and all subjects signed a written informed consent and completed a health history questionnaire prior to participation.

3.2 Experimental Design

A within subjects design was used for this study. The subjects visited the laboratory on three occasions including a familiarization session, as well as randomly ordered 30% 1-RM and 70% 1-RM protocols that include repeated unilateral CON-only DCER leg extensions to failure with the dominant leg (based on kicking preference). In addition, the subjects performed pretest and posttest unilateral CON-only 1-RM tests and MVIC muscle actions (Figure 1) before and after the 30% 1-RM and 70% -1-RM protocols. Each visit was separated by at least 48 hours and the subjects were asked to refrain from performing lower body resistance training between visits.

1-RM	MVIC	Rest	30% or 70% 1-RM Protocol	1-RM	MVIC

Figure 1. Testing order for the 30% and 70% 1-RM fatiguing DCER leg extension protocols.

3.3 One Repetition Maximum and Maximal Voluntary Isometric Contraction

The pretest unilateral CON-only 1-RM tests were performed using the dominant leg and in accordance with to the National Strength and Conditioning Association's guidelines[61]. The subjects performed a warm-up set of five to 10 repetitions at approximately 50% 1-RM, and three to five repetitions at approximately 75% 1-RM. The subjects then performed a series of single repetitions to determine the unilateral CON-only 1-RM within 1.13 kg. The unilateral CON-only 1-RM was defined as the greatest amount of weight that was moved through the full range of motion during the DCER leg extension. The posttest unilateral CON-only 1-RM tests were performed immediately following the 30% and 70% 1-RM protocols. Weight was added until the greatest amount of weight that could successfully be move through the full range of motion was determined (± 1.13 kg). This usually required 2 to 3 trials.

The six second MVIC muscle actions were performed following the unilateral CON-only 1-RM tests at a knee joint angle of 120°[62]. The isometric force production was measured using a custom-fitted load cell (Omegadyne, model LC402, range 0–500 lbs, Stamford, CT) attached to the shin pad of the leg extension machine.

3.4 Fatiguing Protocols

During the 30% 1-RM and 70% 1-RM protocols the subjects performed unilateral CON-only DCER leg extensions to failure with the dominant leg. Failure was defined as the inability to extend the knee to full extension during the CON phase of the leg extension or the inability to complete the CON phase of the leg extension within 1.5 seconds. During each repetition an investigator lowered the lever arm at the end of each CON phase of the leg extension to the starting position to eliminate the ECC phase of the muscle action. All testing was performed on a Hammer Strength Iso-Lateral Leg Extension machine (LifeFitness, Rosemont, IL).

3.5 Electromyography and Mechanomyography

Bipolar electrode arrangements (Ag/AgCl, AccuSensor, Lynn Medical, Wixom, MI, USA) were placed on the VL, VM, and RF of the dominant leg with an interelectrode distance of 30mm during the unilateral CON-only 1-RM tests, MVIC muscle actions, 30% 1-RM protocol, and 70% 1-RM protocol. For the VL, the bipolar electrode arrangements were placed 66% the distance between the anterior superior iliac spine (ASIS) and the lateral border of the patella and orientated at a 20° angle to approximate the pennation angle of the muscle fibers[63,64]. For the VM, the bipolar electrode arrangements were placed 80% the distance between the ASIS and the joint space in front of the anterior border of the medial ligament and orientated at a 53° angle to approximate the pennation angle of the muscle fibers[63]. For the RF, the bipolar electrode arrangements were placed 50% the distance between the ASIS and the superior border of the patella[63]. A reference electrode was placed over the ASIS. The skin was dry shaven, abraded, and cleaned with isopropyl alcohol prior to placing the electrodes. The MMG signal was measured using accelerometers (EGAS-FT-10/V05, Measurement Specialties, Inc., Hampton, VA) placed between the bipolar electrode arrangements on the VL, VM, and RF using double-sided adhesive foam tape.

3.6 Signal Processing

The EMG and MMG signals were zero-meaned and bandpass filtered (fourth-order Butterworth) at 10-500 Hz and 5-100 Hz, respectively. The EMG amplitude (root mean square: RMS), EMG frequency (mean power frequency: MPF), MMG RMS, and

MMG MPF values were calculated between a knee joint angles of 110° and 160° during each unilateral CON-only 1-RM test, as well as for each repetition at every 10% of the repetitions to failure during the 30% 1-RM and 70% 1-RM protocols. A goniometer was placed along the long axis of the femur and tibia of each subject to determine the knee joint angle throughout the range of motion. The EMG RMS, EMG MPF, MMG RMS, and MMG MPF values were normalized as a percent of the first repetition to examine the time course of changes in neuromuscular parameters during the unilateral CON-only DCER leg extensions to failure at 30% 1-RM and 70% 1-RM. Repetitions were normalized as a percentage of the total repetitions completed and if the percent to failure was between repetitions, the repetition immediately following were selected (i.e., if 10% of the time to failure was at repetition 5.5, repetition six was used as the 10% of the time to failure). The EMG RMS, EMG MPF, MMG RMS, and MMG MPF from the MVIC muscle actions were calculated from a two second time period corresponding to the middle 33% of each six second MVIC. All signal processing was performed using custom programs written with LabVIEW programming software (Version 15.0, National Instruments, Austin TX).

3.7 Statistical Analysis

3.7.1 Time Course of Changes in Neuromuscular Parameters

Polynomial regression analyses were used to determine whether there were significant linear, quadratic, or cubic relationships for the normalized EMG RMS, EMG MPF, MMG RMS, and MMG MPF from the VL, VM, and RF versus normalized repetition to failure (% total repetitions) relationships for the composite data of all subjects. Eight, separate, 3 (muscle: VL, VM, and RF) by 2 (Protocol: 30% 1-RM and

70% 1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVAs were performed to compare the EMG RMS, EMG MPF, MMG RMS, and MMG MPF from the unilateral CON-only 1-RM strength and MVIC force. When appropriate, separate, 2 (Protocol: 30% 1-RM protocol and 70% 1-RM protocol) by 2 (Time: pretest and posttest) repeated measures or 3 (Muscle: VL, VM, and RF) by 2 (Protocol: 30% 1-RM and 70% 1-RM) repeated measures ANOVAs were performed to compare the EMG RMS, EMG MPF, MMG RMS, MMG MPF, unilateral CON-only 1-RM strength, and MVIC force from the pretest versus posttest measurements. Twenty-four, separate, one-way repeated measure ANOVAs, each neuromuscular parameter by time (% repetition to failure), were performed to determine the time course of changes in EMG RMS, EMG MPF, MMG RMS, and MMG MPF from the VL, VM, and RF with Student Newman-Keuls post-hoc tests performed when appropriate. An alpha of $p \leq 0.05$ was considered statistically significant for all statistical analyses (SPSS Version 22.0, Armonk, NY).

Chapter IV

Results

4.1 30 versus 70% 1-RM Protocols Repetitions to Failure

Table 1 shows the descriptive statistics for the amount of weight lifted, repetitions completed, and pretest to posttest 1-RM strength and MVIC force measurements for the 30 and 70% 1-RM protocols. Table 2 shows the descriptive statistics for the pretest to posttest neuromuscular responses during the 1-RM and MVIC measurements for the 30 and 70% 1-RM protocols.

Table 1. Discriptive statistics (mean ± SD) for the weight lifted during the dynamic constant external resistance (DCER) leg extension muscle actions to failure, number of repetitions completed, pretest to posttest strength during the 1 repetition maximum (1-RM), and pretest to posttest maximal voluntary isometrc contraction (MVIC) force measurements for the 30 and 70% 1-RM protocols.

	Protocol	
	30% 1-RM	70% 1-RM
Weight Lifted (kg)	14.2 ± 3.2	32.0 ± 7.6
Repetitions Completed	54.8 ± 19.2	14.8 ± 4.4
Pretest 1-RM Strength (kg)	46.5 ± 10.7	45.6 ± 10.5
Posttest 1-RM Strength (kg)	12.7 ± 3.0	29.2 ± 6.7
Pretest MVIC force (kg)	72.1 ± 17.8	71.4 ± 16.6
Posttest MVIC Force (kg)	49.9 ± 11.9	63.5 ± 14.2

4.2 Pretest versus Posttest for Strength and Neuromuscular parameters during the 1-RM Tests

4.2.1 1-RM Strength

The 2 (Protocol: 30% 1-RM and 70% 1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVA for 1-RM values indicated a significant protocol by time interaction. Post-hoc analyses indicated that 1-RM strength decreased significantly from pretest to posttest for both the 30% 1-RM and 70% 1-RM protocols (Figure 2). There was no significant difference between 30% 1-RM and 70% 1-RM pretest strength values. There was, however, a significant difference between the 30% and 70% 1-RM posttest strength (70% 1-RM > 30% 1-RM) (Figure 2).

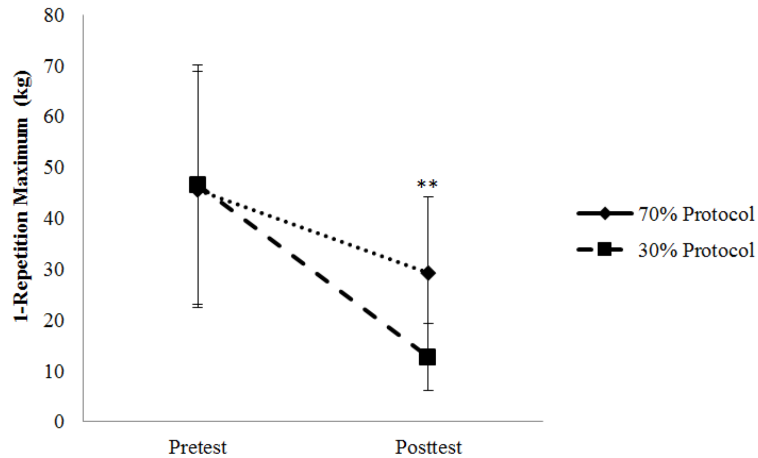

Figure 2. Pretest to posttest 1 repetition maximum (1-RM) strength for the 30 and 70% 1-RM protocols. * Indicates significantly less then pretest.

4.2.2 1-RM EMG RMS

The results of the 3 (muscle: VL, VM, and RF) by 2 (Protocol: 30% 1-RM and 70% 1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVA for EMG RMS indicated no significant interactions or main effects. (Table 1).

4.2.3 1-RM MMG RMS

The results of the 3 (muscle: VL, VM, and RF) by 2 (Protocol: 30% 1-RM and 70% 1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVA for MMG RMS indicated no significant interactions or main effects. (Table1).

4.2.4 1-RM EMG MPF

The results of the 3 (muscle: VL, VM, and RF) by 2 (Protocol: 30% 1-RM and 70% 1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVA for EMG MPF indicated a significant 3-way interaction. The follow up 2 (Protocol: 30% 1-RM and 70%

1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVAs by muscle for EMG MPF from the VL indicated a significant 2-way interaction. Post-hoc analyses indicated that pretest were greater than posttest EMG MPF values for both the 30% 1-RM and 70% 1-RM protocols (Table 1). For the VM there was no significant 2-way interactions, but there was a significant main effect for time (pretest > posttest). For the RF there was a significant 2-way interaction. Post-hoc analyses indicated that pretest were greater than posttest EMG MPF values for the 30 and 70% 1-RM protocols.

4.2.5 1-RM MMG MPF

The results of the 3 (muscle: VL, VM, and RF) by 2 (Protocol: 30% 1-RM and 70% 1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVA for MMG MPF indicated no significant 3-way interaction, but a significant 2-way interaction for protocol by time (Table 1). The follow up 2 (Protocol: 30% 1-RM and 70% 1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVA (collapsed across muscle) for MMG MPF indicated a significant 2-way interaction. Post-hoc analyses indicated that there was no significant difference between pretest and posttest MMG MPF values for the 30% 1-RM protocol, however, there was a significant decrease from pretest to posttest for the 70% 1-RM protocol.

4.3 Pretest versus Posttest for Torque and Neuromuscular parameters during the MVIC Tests

4.3.1 MVIC Torque

The 2 (Protocol: 30% 1-RM and 70% 1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVA for MVIC torque indicated a significant 2-way interaction.

Post-hoc analyses indicated that MVIC torque decreased significantly from pretest to posttest for both the 30% 1-RM and 70% 1-RM protocols (Figure 3). There was no significant different between 30% 1-RM pretest and 70% 1-RM pretest MVIC torque values. There was, however, a significant difference between the 30% 1-RM and 70% 1-RM posttest MVIC torque values (70% 1-RM > 30% 1-RM) (Figure 3).

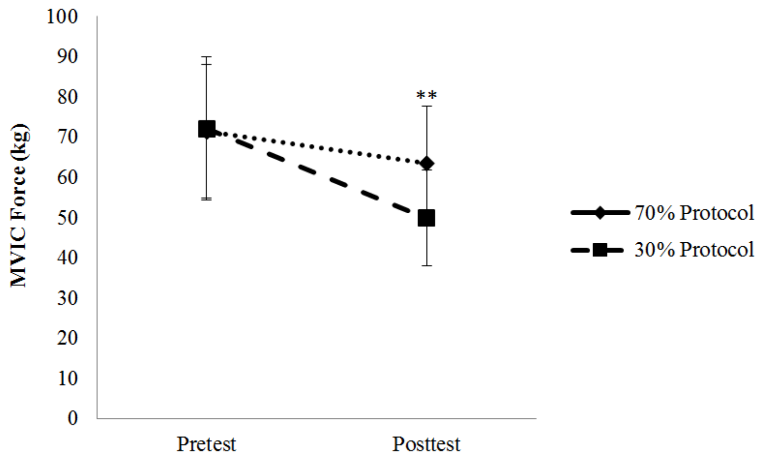

Figure 3. Pretest to posttest maximal voluntary isometric contraction (MVIC) force for the 30 and 70% 1 repetitions maximum (1-RM) protocols. * Indicates significantly less then pretest.

4.3.2 MVIC EMG RMS

The results of the 3 (muscle: VL, VM, and RF) by 2 (Protocol: 30% 1-RM and 70% 1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVA for EMG RMS indicated no significant 3-way interaction, but a significant 2-way interaction for muscle by time (Table 2). The follow up 3 (Muscle: VL, VM, and RF) by 2 (Time: pretest and posttest) repeated measure ANOVA (collapsed across protocol) for EMG RMS indicated a significant 2-way interaction. Post-hoc analyses indicated that there were no significant differences between pretest and posttest EMG RMS values for the VL, VM, and RF.

4.3.3 MVIC EMG MPF

The results of the 3 (muscle: VL, VM, and RF) by 2 (Protocol: 30% 1-RM and 70% 1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVA for EMG MPF indicated no significant 3-way interaction, but significant 2-way interactions for protocol by time and muscle by time (Table 2). Separate follow up 2 (Protocol: 30% 1-RM and 70% 1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVAs for EMG MPF for each muscle indicated significant 2-way interactions for the VL, VM, and RF. Post-hoc analyses indicated that pretest were greater than the posttest EMG MPF values from the VL, VM, and RF for the 30% 1-RM and 70% 1-RM protocol.

4.3.4 MVIC MMG RMS

The results of the 3 (muscle: VL, VM, and RF) by 2 (Protocol: 30% 1-RM and 70% 1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVA for MMG RMS indicated no significant 3-way interaction, but a significant 2-way interaction for muscle by time (Table 2). The follow up 3 (Muscle: VL, VM, and RF) by 2 (Time: pretest and posttest) repeated measures ANOVA (collapsed across protocol) for MMG RMS indicated a significant 2-way interaction. Post-hoc analyses indicated that pretest were greater than posttest MMG RMS values from the VL, VM, and RF.

4.3.5 MVIC MMG MPF

The results of the 3 (muscle: VL, VM, and RF) by 2 (Protocol: 30% 1-RM and 70% 1-RM) by 2 (Time: pretest and posttest) repeated measures ANOVA for MMG MPF indicated no significant 3-way interaction, but a significant 2-way interaction for muscle by time (Table 1). The follow up 3 (Muscle: VL, VM, and RF) by 2 (Time: pretest and posttest) repeated measures ANOVA (collapsed across protocol) for MMG MPF indicated a significant 2-way interaction. Post-hoc analyses indicated that pretest were greater than posttest MMG MPF values from the VL, VM, and RF.

Table 2. Discriptive statistics (mean ± SD) for the electromyographic (EMG) amplitude (root mean square; RMS), EMG mean power frequency (MPF), mechanomyographic (MMG) RMS, and MMG MPF for the pretest to posttest 1 repetitions maximum (1-RM) and maximal voluntary isometric contraction (MVIC) muscle actions from the 30 and 70% 1-RM protocols for the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF).

		1-RM Measurements				MVIC Measurements			
		30% 1-RM		70% 1-RM		30% 1-RM		70% 1-RM	
		Pretest	Posttest	Pretest	Posttest	Pretest	Posttest	Pretest	Posttest
EMG RMS (μV)	VL	694 ± 226	791 ± 318	760 ± 209	790 ± 347	673 ± 192	603 ± 226	636 ± 233	639 ± 286
	VM	810 ± 463	845 ± 460	765 ± 354	795 ± 377	662 ± 324	710 ± 454	623 ± 309	664 ± 335
	RF	607 ± 320	586 ± 208	601 ± 313	596 ± 363	421 ± 140	442 ± 168	467 ± 210	531 ± 436
MMG RMS ($m \cdot s^2$)	VL	0.67 ± 0.26	0.63 ± 0.19	0.59 ± 0.28	0.67 ± 0.45	0.71 ± 0.30	0.45 ± 0.24	0.65 ± 0.24	0.47 ± 0.31
	VM	0.46 ± 0.13	0.43 ± 0.09	0.46 ± 0.13	0.48 ± 0.22	0.56 ± 0.23	0.31 ± 0.13	0.51 ± 0.18	0.34 ± 0.15
	RF	0.54 ± 0.20	0.52 ± 0.19	0.48 ± 0.14	0.51 ± 0.22	0.45 ± 0.14	0.38 ± 0.19	0.42 ± 0.13	0.35 ± 0.17
EMG MPF (Hz)	VL	84 ± 11	54 ± 9	78 ± 8	58 ± 9	80 ± 7	59 ± 11	82.3 ± 6	62 ± 6
	VM	78 ± 19	60 ± 12	81 ± 18	71 ± 12	72 ± 17	60 ± 14	74 ± 15	64 ± 13
	RF	115 ± 30	72 ± 18	112 ± 29	94 ± 24	115 ± 19	86 ± 19	114 ± 27	96 ± 23
MMG MPF (Hz)	VL	16.9 ± 6.4	17.3 ± 5.3	20.4 ± 6.5	16.5 ± 6.8	27.4 ± 8.3	17.7 ± 4.6	28.0 ± 7.4	19.6 ± 5.2
	VM	20.7 ± 10.1	19.1 ± 5.8	19.8 ± 7.9	16.5 ± 3.7	22.7 ± 5.2	16.5 ± 4.6	21.5 ± 3.8	19.1 ± 6.4
	RF	16.0 ± 5.3	16.0 ± 5.6	16.5 ± 7.8	14.1 ± 4.3	24.5 ± 8.2	18.7 ± 7.9	26.1 ± 7.2	20.1 ± 13.1

4.4 Time Course of Changes in Neuromuscular Parameters During 30% 1-RM Muscle Actions to Failure

Figure 4 shows the results of the polynomial regression analyses and one-way repeated measure ANOVAs with post-hoc Student Newman-Keuls tests for the normalized EMG RMS, EMG MPF, MMG RMS, and MMG MPF versus repetition relationships from the VL at 30% 1-RM. There were significant cubic relationships for the EMG RMS (R^2 = 0.98) and MMG RMS (R^2 = 0.63) versus repetition from the VL at 30% 1-RM that were greater than the initial repetition from 10 to 100% of the total repetitions (Figure 4). There were significant negative quadratic relationships for EMG MPF (R^2 = 0.96) and MMG MPF (R^2 = 0.94) versus repetition from the VL at 30% 1-RM that began to decrease from the initial repetition at 20 and 60% to 100% of the total repetitions, respectively (Figure 4).

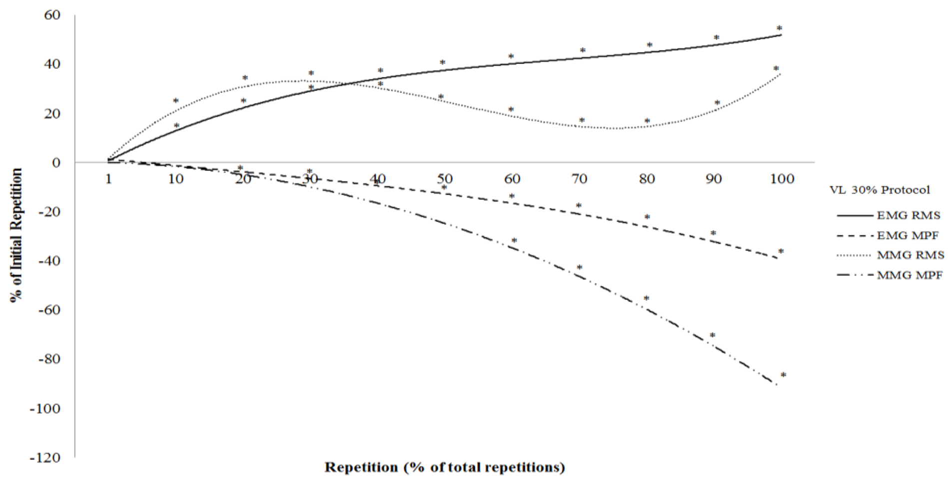

Figure 4. Time course of changes in neuromuscular responses from the vastus lateralis (VL) during the 30% 1-RM protocol. * Indicates significantly different than the initial repetition.

Figure 5 shows the results of the polynomial regression analyses and one-way repeated measure ANOVAs with post-hoc Student Newman-Keuls tests for the normalized EMG RMS, EMG MPF, MMG RMS, and MMG MPF versus repetition relationships from the VM at 30% 1-RM. There were significant cubic relationships for the EMG RMS (R^2 = 0.95) and MMG RMS (R^2 = 0.67) versus repetition from the VM at 30% 1-RM that were greater than the initial repetition from 10 to 100% of the total repetitions (Figure 5). There were significant negative quadratic relationships for EMG MPF (R^2 = 0.97) and MMG MPF (R^2 = 0.91) versus repetition from the VM at 30% 1-RM that began to decrease from the initial repetition at 90 and 60% to 100% of the total repetitions, respectively (Figure 5).

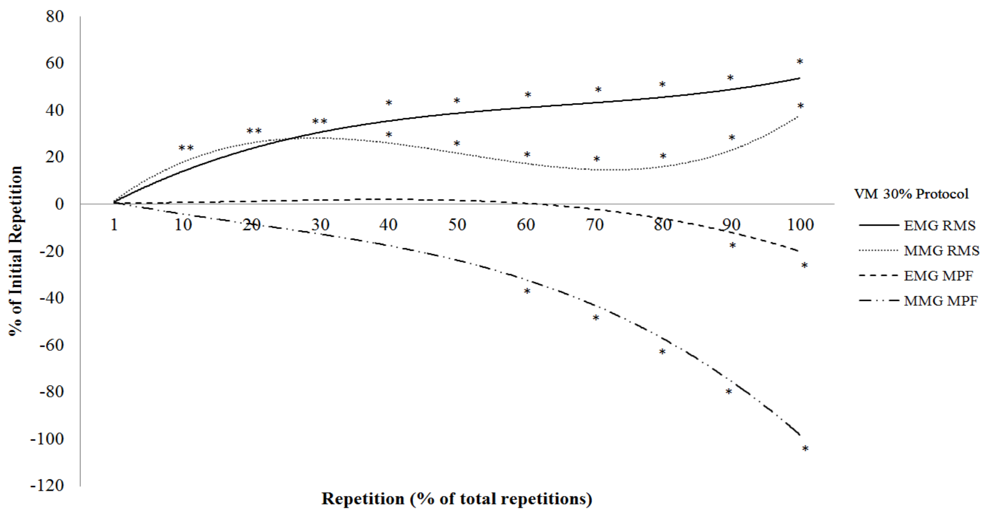

Figure 5. Time course of changes in neuromuscular responses from the vastus medialis (VM) during the 30% 1-RM protocol. * Indicates significantly different than the initial repetition.

Figure 6 shows the results of the polynomial regression analyses and one-way repeated measure ANOVAs with post-hoc Student Newman-Keuls tests for the normalized EMG RMS, EMG MPF, MMG RMS, and MMG MPF versus repetition relationships from the RF at 30% 1-RM. There were significant cubic relationships for the EMG RMS (R^2 = 0.97) and MMG RMS (R^2 = 0.77) versus repetition from the RF at 30% 1-RM that were greater than the initial repetition from 10 to 100% of the total repetitions (Figure 6). There were significant negative quadratic relationships for EMG MPF (R^2 = 0.95) and MMG MPF (R^2 = 0.91) versus repetition from the RF at 30% 1-RM that began to decrease from the initial repetition at 60 and 30% to 100% of the total repetitions, respectively (Figure 6).

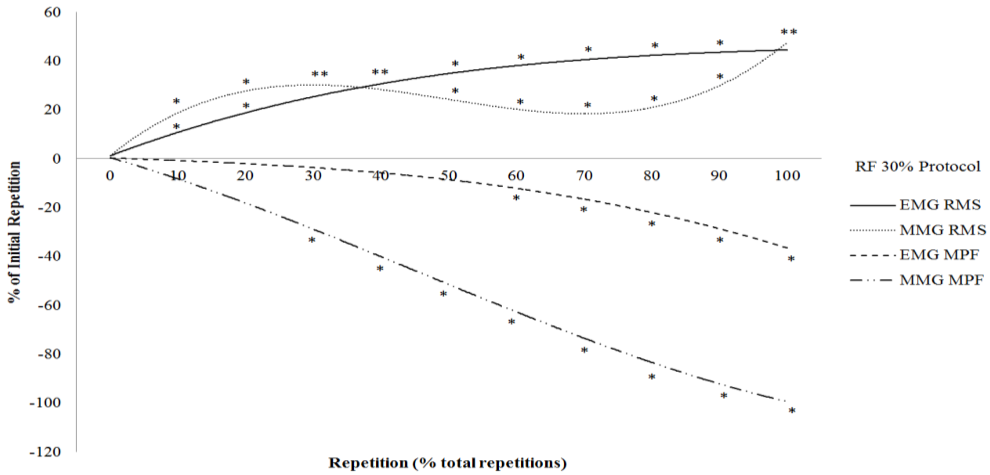

Figure 6. Time course of changes in neuromuscular responses from the rectus femoris (RF) during the 30% 1-RM protocol. * Indicates significantly different than the initial repetition.

4.5 Time Course of Changes in Neuromuscular Parameters During 70% 1-RM Muscle Actions to Failure

Figure 7 shows the results of the polynomial regression analyses and one-way repeated measure ANOVAs with post-hoc Student Newman-Keuls tests for the normalized EMG RMS, EMG MPF, MMG RMS, and MMG MPF versus repetition relationships from the VL at 70% 1-RM. There were significant cubic relationships for the EMG RMS (R^2 = 0.98) and MMG RMS (R^2 = 0.89) versus repetition from the VL at 70% 1-RM that were greater than the initial repetition from 10 to 100% of the total repetitions (Figure 7). There was a significant negative quadratic relationship for EMG MPF (R^2 = 0.98) versus repetition from the VL at 70% 1-RM that decreased from the initial repetition from 60 to 100% of the total repetitions (Figure 7). There was a significant cubic relationship for MMG MPF (R^2 = 0.90) versus repetition from the VL at 70% 1-RM that decreased from the initial repetition from 10 to 100% of the total repetitions (Figure 7).

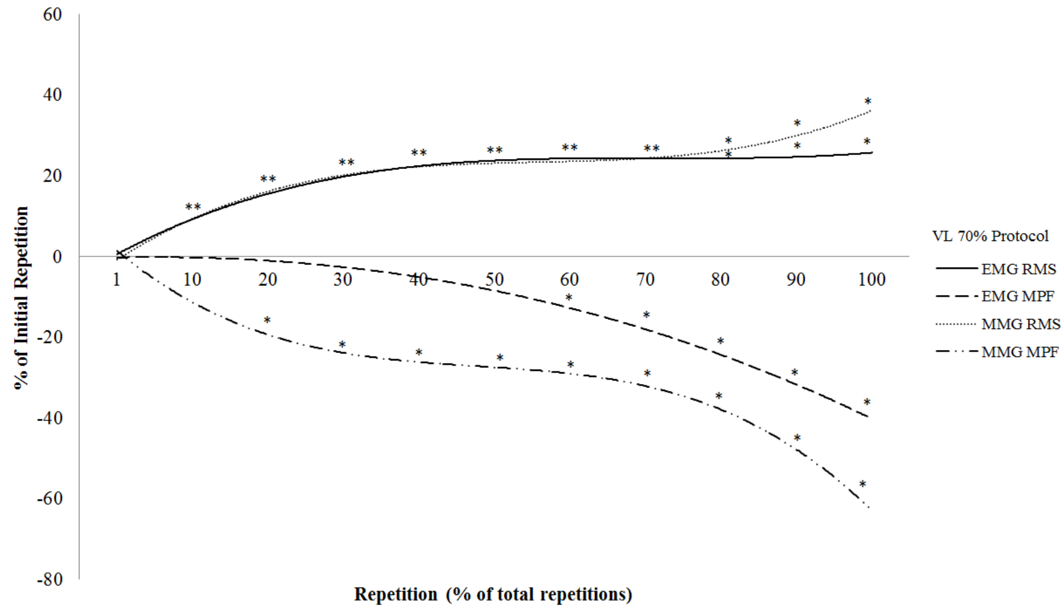

Figure 7. Time course of changes in neuromuscular responses from the vastus lateralis (VL) during the 70% 1-RM protocol. * Indicates significantly different than the initial repetition.

Figure 8 shows the results of the polynomial regression analyses and one-way repeated measure ANOVAs with post-hoc Student Newman-Keuls tests for the normalized EMG RMS, EMG MPF, MMG RMS, and MMG MPF versus repetition relationships from the VM at 70% 1-RM. There was a significant positive quadratic relationship for the EMG RMS (R^2 = 0.97) versus repetition from the VM at 70% 1-RM that was greater than the initial repetition from 20 to 100% of the total repetitions (Figure 8). There was a significant positive linear relationship for the MMG RMS (R^2 = 0.45) versus repetition from the VM at 70% 1-RM that was greater than the initial repetition from 20 to 100% of the total repetitions (Figure 8). There were significant negative quadratic relationships for EMG MPF (R^2 = 0.96) and MMG MPF (R^2 = 0.84) versus repetition from the VM at 70% 1-RM that began to decrease from the initial repetition at 80 and 20% to 100% of the total repetitions, respectively (Figure 8).

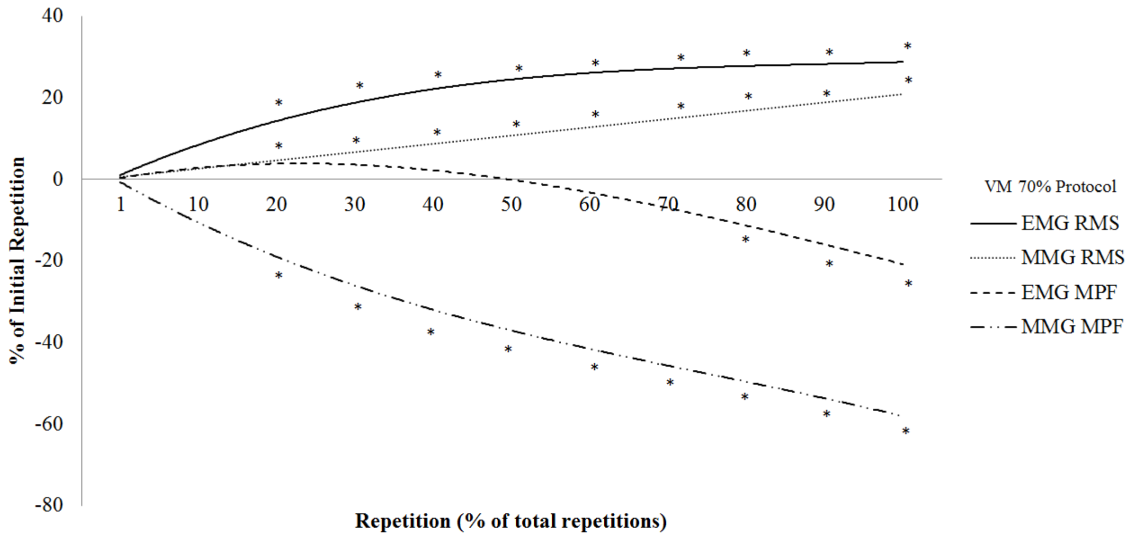

Figure 8. Time course of changes in neuromuscular responses from the vastus medialis (VM) during the 70% 1-RM protocol. * Indicates significantly different than the initial repetition.

Figure 9 shows the results of the polynomial regression analyses and one-way repeated measure ANOVAs with post-hoc Student Newman-Keuls tests for the normalized EMG RMS, EMG MPF, MMG RMS, and MMG MPF versus repetition relationships from the RF at 70% 1-RM. There was a significant cubic relationship for the EMG RMS (R^2 = 0.96) versus repetition from the RF at 70% 1-RM that was greater than the initial repetition from 10 to 100% of the total repetitions (Figure 9). There was a significant positive linear relationship for the MMG RMS (R^2 = 0.48) versus repetition from the RF at 70% 1-RM that was greater than the initial repetition from 10 to 100% of the total repetitions (Figure 9). There were significant negative quadratic relationships for EMG MPF (R^2 = 0.96) and MMG MPF (R^2 = 0.92) versus repetition from the RF at 70% 1-RM that began to decrease from the initial repetition at 80 and 70% to 100% of the total repetitions, respectively (Figure 9).

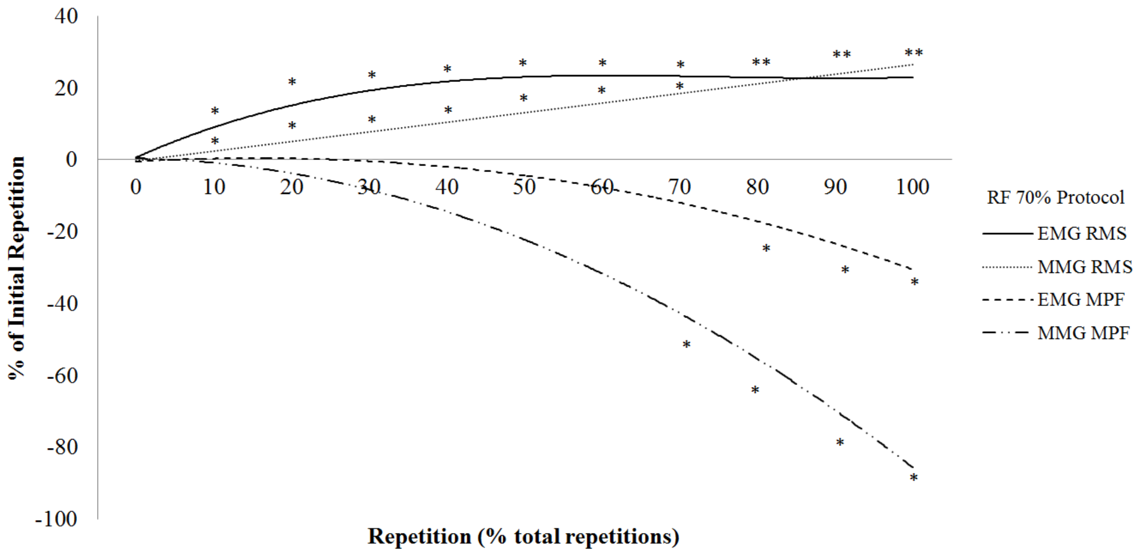

Figure 9. Time course of changes in neuromuscular responses from the rectus femoris (RF) during the 70% 1-RM protocol. * Indicates significantly different than the initial repetition.

Chapter V

Discussion

5.1 Neuromuscular Responses and Force from Pretest to Posttest Measurements

5.1.1 1-RM Strength and Neuromuscular Responses from Pretest to Posttest excrement

In the present study, there were 76 and 36% decreases in 1-RM strength after the 30 and 70% 1-RM protocols, respectively, but no changes in EMG RMS or MMG RMS from the VL, VM, or RF following either protocol (Figure 2). The EMG MPF, however, decreased from all three muscles following both protocols (Table 2). There were no changes in MMG MPF from any of the muscles following the 30% 1-RM protocol, but there were decreases from all muscles following the 70% 1-RM protocol (Table 2). These findings were in agreement with Pincivero et al.[39] who reported no pretest to posttest changes in EMG RMS during 1-RM measurements, but decreases in EMG MPF from the VL, VM, and RF after DCER leg extension muscle actions to failure at 50% 1-RM. These findings were also in agreement with Akima et al.[16] who reported no changes in EMG RMS from the VL, VM, and RF after DCER leg extension muscle actions to failure at 50 and 70% 1-RM. It was suggested[16,39] that the decrease in pretest to posttest strength, without changes in EMG RMS, were a result of excitation contraction coupling failure. Thus, the current findings were in agreement with previous studies[39,16] which suggested no changes in muscle activation (EMG RMS), but decreases in MUAP CV (EMG MPF) during the 1-RM measurements following submaximal, DCER leg extension muscle actions to failure. The current findings suggested intensity-specific (30 versus 70% 1-RM) differences in MMG MPF patterns following fatiguing, submaximal DCER leg extension workbouts to failure that likely reflected differences in motor unit firing rate responses.

5.1.2 MVIC Torque and Neuromuscular Responses from Pretest to Posttest

In the present study, there were 14 and 11% decreases in MVIC torque after the 30 and 70% 1-RM protocols, respectively. In addition, there were no changes in pretest to posttest EMG RMS values from the VL, VM, and RF, but increases in MMG RMS from all three muscles after both the 30 and 70% 1-RM protocols (Figure 3). The EMG MPF and MMG MPF, however, decreased from pretest to posttest for the VL, VM, and RF after both the 30 and 70% 1-RM protocols (Table 2). These findings were not in agreement with the findings of Croce et al.[65] who reported a 76% pretest to posttest decrease in MVIC torque that was accompanied by decreases in MMG RMS (55, 60, and 39%), EMG MPF (20, 20, and 36%), and MMG MPF (22, 18, and 30%) from the VL, VM, and RF, respectively, but no changes in EMG RMS following CON-only, maximal, isokinetic leg extension muscle actions to failure. The increase in MMG RMS in the current study, but decrease in MMG RMS reported by Croce et al.[65] may be due to mode- (DCER versus isokinetic) and/or intensity-specific (maximal versus submaximal) differences in the neuromuscular responses.

In the current study, both protocols resulted in decreases in pretest to posttest 1-RM strength and MVIC force. In addition, all three muscles had the same neuromuscular responses during the 30 and 70% 1-RM protocols for both the 1-RM and MVIC measurements. There were, however, intensity-specific (30 versus 70% 1-RM) differences in the neuromuscular responses during the 1-RM measurements which suggested that the 70% protocol resulted in a fatigue-induced decreases in MMG MPF, which reflects global motor unit firing rate, but not the 30% 1-RM protocol. During the MVIC measurements there were increases in MMG RMS, decreases in MMG MPF and EMG MPF, but no changes in EMG RMS after both the 30 and 70% 1-RM protocols. These neuromuscular responses suggested increases in motor unit recruitment (MMG RMS), but decreases in global motor unit firing rate (MMG MPF) and MUAP CV (EMG MPF) during the MVIC measurements after both the 30 and 70% 1-RM protocol. Therefore, there were no muscle-related differences in neuromuscular responses, but were mode- and intensity-specific, pretest to posttest neuromuscular responses as a result of the fatiguing DCER workbouts when measured during 1-RM versus MVIC muscle actions.

5.2 30% 1-RM Protocol Time Course of Changes in Neuromuscular Responses

5.2.1 Vastus Lateral: 30% 1-RM Protocol

The results of the present study indicated four unique phases (1 to 20, 20 to 60, 60 to 80, and 80 to 100% of repetitions to failure) of the neuromuscular responses from the VL during the 30% 1-RM protocol (Figure 4). During the first 20% of the repetitions to failure there were increases in EMG RMS and MMG RMS, but no changes in EMG MPF or MMG MPF. These findings were similar to Gonzalez-Izal et al.[66] who reported a 45% increase in EMG RMS, but no change in EMG MPF during the first 10 of 20 maximal CON-only isokinetic leg extension muscle actions. Thus, the neuromuscular responses in the present study suggested that during the first 20% of the repetitions to failure there were increases in muscle activation and motor unit recruitment, but no changes in MUAP CV or global motor unit firing rate. From 20 to 60% of the repetitions to failure there was an increase in EMG RMS, decreases in MMG RMS and EMG MPF, but no change in

MMG MPF. These findings were similar to Ebersole et al.[67] who reported an increase in EMG RMS, decrease in MMG RMS and EMG MPF, but no change in MMG MPF from the VL during 50 CON-only isokinetic leg extension muscle actions. Ebersole et al.[67] suggested that the decrease in MMG RMS was likely due to intramuscular fluid pressure having a greater effect than increases in recruitment on the MMG signal. Specifically, during prolonged static and dynamic muscle actions, increasing intramuscular fluid pressure may restrict the lateral muscle fiber oscillations, decreasing MMG RMS. Therefore, the decrease in MMG RMS from 20 to 60% of the repetitions to failure may have reflected a balance of competing effects of motor unit recruitment (which can increase MMG RMS) and intramuscular fluid pressure (which can decrease MMG RMS) acting on the MMG signal[68]. The decrease in EMG MPF suggested a buildup of metabolic byproducts that slowed MUAP CV[59], which further supported the fatiguing nature of the workbout. During 60 to 80% of the repetitions to failure there was an increase in EMG RMS, but decreases in MMG RMS, EMG MPF, and MMG MPF. These findings were similar to Jenkins et al.[7] and Pincivero et al.[39] who reported increases in EMG RMS and decreases in EMG MPF during DCER leg extensions to failure at 30 and 50% 1-RM, respectively. The continued decrease in MMG RMS, in the present study, suggested that intramuscular fluid pressure still had a greater affect than recruitment on the MMG signal. In addition, unlike 20 to 60% of the repetitions to failure, there was a decrease in MMG MPF that suggested a decrease in the global firing rate of the activated motor units during 60 to 80% of the repetition to failure. It has been suggested[69,70] that a decrease in global motor unit firing rate allows for a greater fusion of activated motor units to maintain the required force. During the final phase (80 to 100% of the repetitions to failure) there were increases in EMG RMS and MMG RMS, and decreases in EMG MPF and MMG MPF. These findings were similar to previous studies[7,66,67] of dynamic leg extension muscle actions that have reported increases in EMG RMS and MMG RMS, as well as decreases in EMG MPF and MMG MPF. For example, Ebersole et al.[67] reported an increase in EMG RMS and MMG RMS, but decreases in EMG MPF and MMG MPF from the VL during the final 10 of 50 CON-only isokinetic leg extension muscle actions. Thus, the increase in MMG RMS from 80 to 100% of the repetitions to failure in the present study suggested that the increases in recruitment overcame the competing influences of intramuscular fluid pressure on the MMG signal. In addition, the continued decrease in MMG MPF suggested that the decrease in global motor unit firing rate persisted to failure. Therefore, during the 30% 1-RM protocol, the VL exhibited four unique phases (1 to 20, 20 to 40, 60 to 80, and 80 to 100%) of neuromuscular responses that contributed to the overall force production of the quadriceps femoris during CON-only DCER leg extension muscle actions to failure.

5.2.2 Vastus Medialis: 30% 1-RM Protocol

The results of the present study indicated four unique phases (1 to 30, 30 to 60, 60 to 90, and 90 to 100% of the repetitions to failure) of the neuromuscular responses from the VM during the 30% 1-RM protocol (Figure 5). During the first 30% of the repetitions to failure there were increases in EMG RMS and MMG RMS, but no change in EMG MPF or MMG MPF. These findings were different than those of Pincivero et al.[39] who reported an increase in EMG RMS, but decrease in EMG MPF from the VM during the first 30% of DCER leg extensions to failure at 50% 1-RM. In addition, these findings were different than those of Ebersole et al.[67] who reported increases in EMG RMS and

MMG RMS, decreases in MMG MPF, and no change in EMG MPF from the VM during the first 15 of 50 maximal CON-only isokinetic muscle actions of the leg extensors. These findings[40,67] suggested mode- (isokinetic versus DCER) and intensity-related (maximal versus submaximal) differences in neuromuscular responses during dynamic muscle actions. During the second phase (30 to 60% of the repetitions to failure) there was an increase in EMG RMS, decrease in MMG RMS, and no changes in EMG MPF or MMG MPF. The MMG RMS responses were similar to Ebersole et al.[67] who reported a decrease in MMG RMS from the VM during repetitions 15 to 40 of 50 maximal CON-only isokinetic leg extension muscle actions. The decrease in MMG RMS was likely a result of intramuscular fluid pressure having a greater affect than motor unit recruitment on the MMG signal. In addition, these findings were similar to the neuromuscular patterns exhibited by the VL during the middle phase of the 30% 1-RM protocol and, therefore, further supported the increase in intramuscular fluid pressure during the middle phases of the fatiguing workbout. During the third phase (60 to 90% of the repetitions to failure), however, there were increases in EMG RMS and MMG RMS, decrease in MMG MPF, but no change in EMG MPF. These findings were similar to Ebersole et al.[67] who reported increases in EMG RMS, MMG RMS, decrease in MMG MPF, and no change in EMG MPF from the VM during repetitions 40 to 50 of 50 maximal CON-only isokinetic muscle actions of the leg extensors. The increases in EMG RMS and MMG RMS suggested that motor unit recruitment overcame the competing effects of intramuscular fluid pressure on the MMG signal[67]. In addition, the decrease in MMG MPF suggested a decrease in the global motor unit firing rate of activated motor units[69,70]. During the final phase (90 to 100% of the repetitions to failure) there were increases in EMG RMS and

MMG RMS, but decreases in EMG MPF and MMG MPF. These findings were similar to Jenkins et al.[7] who reported an increase in EMG RMS and decrease in EMG MPF from the VM during DCER leg extension muscle actions to failure at 30% 1-RM. In addition, these findings were similar to Pincivero et al.[39] who reported increases in EMG RMS and decreases in EMG MPF from the VM during the CON phase of DCER leg extension muscle actions to failure at 50% 1-RM. The decrease in EMG MPF in the present study suggested a buildup of metabolic byproducts that slowed MUAP CV, which further supported the fatiguing nature of the workbout. Therefore, during the 30% 1-RM protocol the VM exhibited four unique phases (1 to 30, 30 to 60, 60 to 90, and 90 to 100%) of neuromuscular responses that contributed to the overall force production of the quadriceps femoris during CON-only DCER leg extension muscle actions to failure.

5.2.3 Rectus Femoris: 30% 1-RM Protocol

The results of the present study indicated three unique phases (1 to 30%, 30 to 60%, and 60 to 100% of repetition to failure) of the neuromuscular responses from the RF during the 30% 1-RM protocol (Figure 6). During the first 30% of the repetitions to failure there were increases in EMG RMS and MMG RMS, but no changes in EMG MPF or MMG MPF. These findings were not consistent with those of Pincivero et al.[39] who reported an increase in EMG RMS and decrease in EMG MPF from the RF during the first 30% of DCER leg extensions to failure at 50% 1-RM. The current findings were also not consistent with those of Ebersole et al.[67] who reported increases in EMG RMS and MMG RMS, but decreases in EMG MPF and MMG MPF from the RF during the first 15 of 50 maximal CON-only isokinetic muscle actions of the leg extensors. Together, the current and previous studies[7,40,67] suggest mode- (isokinetic versus DCER) and intensity-related (maximal versus submaximal) differences in the neuromuscular responses during the initial 30% of a fatiguing workbout. During 30 to 60% of the repetitions to failure there were increases in EMG RMS, decreases in MMG RMS and MMG MPF, and no change in EMG MPF. These findings were similar to those of Jenkins et al.[7] and Pincivero et al.[39] who reported increases in EMG RMS, but decreases in EMG MPF from the RF during DCER leg extension muscle actions to failure at 30 and 50% 1-RM, respectively. In addition, the decrease in MMG RMS in the present study was similar to Ebersole et al.[67] who suggested that the decrease in MMG RMS during the fatiguing muscle actions likely resulted from greater intramuscular fluid pressure. During the final phase (60 to 100% of repetitions to exhaustion) there were increases in EMG RMS and MMG RMS, but decreases in EMG MPF and MMG MPF. These were similar to those of Ebersole et al.[67] who also reported increases in EMG RMS and MMG RMS, but decreases in EMG MPF and MMG MPF from the RF during 50 maximal isokinetic leg extension muscle actions. The decrease in EMG MPF supported the fatiguing nature of the workbout and the increase in MMG RMS suggested that motor unit recruitment overcame the effects of intramuscular fluid pressure on the MMG signal. Thus, during the 30% 1-RM protocol, the RF exhibited three unique (1 to 30, 30 to 60, and 60 to 100% of repetitions to exhaustion) phases of neuromuscular responses that contributed to the overall force production of the quadriceps femoris during CON-only DCER leg extension muscle actions to failure.

5.3 70% 1-RM Protocol Time Course of Changes in Neuromuscular Responses

5.3.1 Vastus Lateral: 70% 1-RM Protocol

In the present study, there were four unique phases (1 to 20, 20 to 60, 60 to 80, and 80 to 100% of the repetitions to failure) of the neuromuscular responses from the VL during the 70% 1-RM protocol (Figure 7). During the first 20% of the repetitions to failure there were increases in EMG RMS and MMG RMS, but no changes in EMG MPF or MMG MPF. These findings were similar to Akima et al.[16] who reported increases in EMG RMS from the VL during the first 25% of repetitions to failure of DCER leg extension muscle actions at 70% 1-RM. These findings were not in agreement with Croce et al.[65] who reported an increase in EMG RMS, but decreases in MMG RMS, EMG MPF, and MMG MPF from the VL during the first 15% of maximal, CON-only isokinetic leg extension muscle actions to failure. Thus, the current study and previous studies[16,65] suggested intensity- (maximal versus submaximal) and mode-specific (isokinetic versus DCER) differences during the first 20% of leg extension repetitions to failure. In addition, these neuromuscular responses suggested an increase in muscle activation and motor unit recruitment, but no changes in global motor unit firing rate or MUAP CV. From 20 to 60% of the repetitions to failure in the present study, there were increases in EMG RMS and MMG RMS, a decrease in MMG MPF, and no change in EMG MPF. These findings were in agreement with Masuda et al.[34] who reported an increase in EMG RMS, but no change in EMG MPF from the VL during 20 to 60% of the repetitions to failure of DCER leg extension muscle actions at 50% 1-RM. In addition, the current findings were in agreement with Akima et al.[16] who reported an increase in EMG RMS from the VL during 25 to 75% of the repetitions to failure of DCER leg extension muscle actions at 70% 1-RM. Therefore, from 20 to 60% of the repetitions to failure there were increases in muscle activation and motor unit recruitment, a decrease in global motor unit firing rate, but no change in MUAP CV during DCER leg extension muscle actions at 70% 1-RM. During the third phase (repetitions 60 to 80% of the repetitions to failure) there was a plateau in EMG RMS and MMG RMS, and decreases in EMG MPF and MMG MPF. These findings were similar to those of Croce et al.[65] who reported a plateau in EMG RMS and MMG RMS, but decrease in EMG MPF and MMG MPF from the VL during 60 to 75% of the repetitions to failure of maximal isokinetic leg extension muscle actions. These findings suggested that from 60 to 80% of the repetitions to failure there was no change in muscle activation or motor unit recruitment, but decreases in global motor unit firing rate and MUAP CV. From 80 to 100% of the repetitions to failure there was a plateau in EMG RMS, an increase in MMG RMS, and decreases in EMG MPF and MMG MPF. These findings were in agreement with Pincivero et al.[39] who reported a plateau in EMG RMS and decreases in EMG MPF from the VL during DCER leg extension muscle actions to failure at 50% 1-RM. Thus, from 80 to 100% of the repetitions to failure there was an increase in motor unit recruitment accompanied by a decrease in global motor unit firing rate and MUAP CV. Therefore, during the 70% 1-RM protocol, the VL exhibited four unique phases (1 to 20, 20 to 60, 60 to 80, and 80 to 100% of the repetition to failure) of fatigue-induced neuromuscular responses that contributed to the overall force production of the quadriceps femoris during CON-only DCER leg extension muscle actions.

5.3.2 Vastus Medialis: 70% 1-RM

The results of the present study indicated three unique phases (1 to 20, 20 to 80, and 80 to 100% of the repetitions to failure) of the neuromuscular responses from the VM during the 70% 1-RM protocol (Figure 8). During the first 20% of the repetitions to failure there were no changes in EMG RMS, MMG RMS, EMG MPF, and MMG MPF from the VM. These findings were not in agreement with Akima et al.[16] who reported an increase in EMG RMS from the VM during the first 25% of the repetitions to failure of DCER leg extension muscle actions to failure at 70% 1-RM. In addition, these findings were not in agreement with Pincivero et al.[39] who reported an increase in EMG RMS and a decrease in EMG MPF from the VM during the first 20% of the repetitions to failure of DCER leg extension muscle actions to failure at 50% 1-RM. The fatigue-related differences in neuromuscular responses may be explained by the differences in protocol. Specifically, the present study only included the CON phase of the leg extension muscle actions, but Akima et al.[16] and Pincivero et al.[39] performed the CON and eccentric (ECC) phases of the leg extension muscle actions. Thus, the confounding effects of the ECC phase following the CON phase may result in earlier fatigue-related changes in the neuromuscular responses than during CON-only DCER leg extension muscle actions. During the middle phase (20 to 80% of the repetitions to failure) there were increases in EMG RMS and MMG RMS, decrease in MMG RMS, but no change in EMG MPF. These findings were in agreement with Akima et al.[16] who reported an increase in EMG RMS from the VM during 25 to 75% of the repetitions to failure of DCER leg extension muscle actions to failure at 70% 1-RM. The current study was not in agreement, however, with Croce et al.[65] who reported a decrease in EMG RMS, MMG RMS, and MMG MPF, but a plateau in EMG MPF from the VM during 15 to 75% of the repetitions to failure of maximal isokinetic muscle actions. The differences in the present study and those of Croce et al.[65] suggested mode- (isokinetic versus DCER) and intensity-related (maximal versus submaximal) differences in neuromuscular responses. Thus, during the middle phase (20 to 80% of the repetitions to failure) there were increases in muscle activation and motor unit recruit that were accompanied by a decrease in global motor unit firing rate. From 80 to 100% of the repetitions to failure there was a plateau in EMG RMS, an increase in MMG RMS, but decreases in EMG MPF and MMG MPF. These findings were similar to those of Akima et al.[16] who reported a plateau in EMG RMS from VM during 75 to 100% of the repetitions to failure of DCER leg extension muscle actions to failure at 70% 1-RM. In addition, these findings were in agreement with Pincivero et al.[39] who reported a plateau in EMG RMS and a decrease in EMG MPF from VM during 80 to 100% of the repetition to failure of DCER leg extension muscle actions at 50% 1-RM. Thus, the neuromuscular responses from 80 to 100% of the repetitions to failure suggested an increase in motor unit recruitment, but decreases in global motor unit firing rate and MUAP CV. Therefore, during the 70% 1-RM protocol there were three unique phases (1 to 20, 20 to 80, and 80 to 100% of the repetitions to failure) of neuromuscular responses that contributed to the overall force production of the quadriceps femoris during CON-only DCER leg extension muscle actions to failure.

5.3.3 Rectus Femoris: 70% 1-RM Protocol

The results of the present study indicated three unique phases (1 to 50, 50 to 70, and 70 to 100% of the repetitions to failure) of the neuromuscular responses from the RF during the 70% 1-RM protocol (Figure 9). During the first 50% of the repetitions to failure there were increases in EMG RMS and MMG RMS, but no changes in EMG MPF or MMG MPF. These findings were not in agreement with Jenkins et al.[7] and Pincivero et al.[39] who reported increases in EMG RMS and decreases in EMG MPF from the RF during the first 50% of the repetitions to failure of DCER leg extension muscle actions at

80 and 50% 1-RM, respectively. The differences in neuromuscular responses in the current study and those of Jenkins et al.[7] and Pincivero et al.[39] may be explained by a protocol-related (CON-only versus CON and ECC) differences in neuromuscular responses and motor unit activation strategies during DCER leg extension muscle actions to failure. Thus, the current neuromuscular response suggested that during the first 50% of the repetitions to failure there were increases in muscle activation and motor unit recruitment, but no changes in global motor unit firing rate or MUAP CV. From 50 to 70% of the repetitions to failure there was a plateau in EMG RMS, an increase in MMG RMS, but no change in EMG MPF or MMG MPF. These findings were in agreement with Akima et al.[16] who reported an increase in EMG RMS from the RF during 25 to 75% of the repetitions to failure of DCER leg extension muscle actions at 70% 1-RM. The current findings were not in agreement with Croce et al.[65], however, who reported decreases in EMG RMS, MMG RMS, and MMG MPF, but a plateau in EMG MPF from the RF during 30 to 75% of the repetitions to failure of maximal, isokinetic leg extension muscle actions. These findings suggested mode- (isokinetic versus DCER) and intensity-related (maximal versus submaximal) differences in the neuromuscular responses from the RF during the middle phase (50 to 70% of the repetitions to failure). In addition, the middle phase (50 to 70% of the repetitions to failure) suggested an increase in motor unit recruitment, a plateau in muscle activation, and no changes in global motor unit firing rate or MUAP CV. During the final phase (70 to 100% of the repetitions to failure), there was a plateau in EMG RMS, an increase in MMG RMS, and decreases in MMG MPF and EMG MPF that began at 70 and 80% of the repetitions to failure, respectively. These findings were in agreement with Pincivero et al.[39] who reported a plateau in EMG RMS,

but a decrease in EMG MPF from the RF during 80 to 100% of the repetitions to failure of DCER leg extensions at 50% 1-RM. In addition, these findings were in agreement with Akima et al.[16] who reported a plateau in EMG RMS from the RF during 75 to 100 of the repetitions to failure of DCER leg extension muscle actions at 70% 1-RM. Thus, from 70 to 100% of the repetitions to failure there was an increase in motor unit recruitment, and no change in muscle activation, but decreases in global motor unit firing rate (at 70% of the repetitions to failure) and MUAP CV (at 80% of the repetitions to failure). Therefore, during the 70% 1-RM protocol, the RF exhibited three unique phases (1 to 50, 50 to 70, and 70 to 100% of the repetitions to exhaustion) of neuromuscular responses that contributed to the overall force production of the quadriceps femoris during CON-only DCER leg extension muscle actions to failure.

5.4 Motor Unit Activation Strategies

There have been a number of fatigue-related motor unit activation strategies[69,71-74] proposed using simulation, stimulation, and voluntary studies. Three commonly used strategies are: 1) After-Hyperpolarization theory (AHP)[71]; 2) Muscle Wisdom theory[69]; and 3) Onion Skin Scheme[73]. Each strategy is characterized by unique neuromuscular responses and suggests that the maintenance or modulation of force during the process of fatigue is determined by a different set of physiological mechanisms.

The AHP theory was based on stimulation studies by Eccles et al.[71] and Kernell et al.[74,75] and is characterized by fatigue-induced increases in muscle activation, motor unit recruitment, and firing rate. According to the AHP theory, a fatigue-related buildup of metabolic byproducts causes a gradient shift from intracellular to extracellular potassium [K^+] and decreases the membrane potential below resting levels following depolarization which has been termed after-hyperpolarization[71,74,75] (Figure 10). The after-hyperpolarization then signals the central nervous system to increase motor unit recruitment and firing rate to maintain force production[76]. Therefore based on the AHP theory, the process of fatigue should be characterized by increases in EMG RMS, MMG RMS, and MMG MPF due to the increases in motor unit recruitment and firing rate.

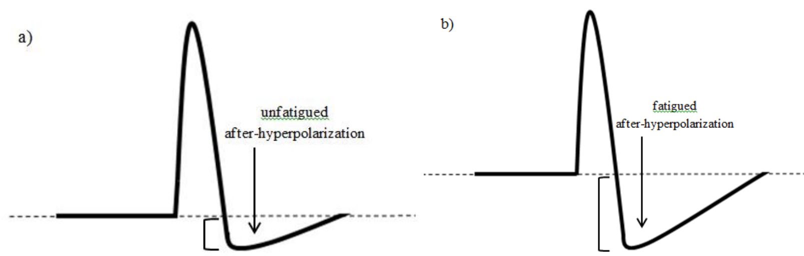

Figure 10. Depiction of a motor unit action potential and the after-hyperpolarization in unfatigued (a) and fatigued (b) muscle. The unfatigued after-hyperpolarization (a) would stimulate lower firing rates of the activated motor units than the fatigued after-hyperpolarization (b).

The Muscle Wisdom theory was based on a stimulation study by Marsden et al.[69] and is characterized by fatigue-induced increases in muscle activation and motor unit recruitment, but decreases in firing rate and MUAP CV. Specifically, during a fatiguing task the Muscle Wisdom theory[69] describes a progressive prolongation of relaxation time and a decrease in motor unit firing rate which, theoretically, allow for greater fusion of motor unit twitches and optimal force production. These findings were supported by Marsden et al.[69] and Bigland-Ritchie et al.[60] who demonstrated that stimulated motor units maintained the greatest force production during a sustained contraction when the frequency of the stimulation was progressively decreased.

The Onion Skin Scheme was based on a simulation study by De Luca and Erim[73] and, like the Muscle Wisdom Theory, is characterized by fatigue-induced increases in muscle activation and motor unit recruitment, but decreases in firing rate and MUAP CV. The Onion Skin Scheme suggests that at any time or force level, earlier recruited motor units have higher firing rates than later recruited motor units. This theory results in an orderly nesting of firing rate curves under one another, which resembles the skin of an onion. Thus, higher threshold motor units require lower firing rates to produce their maximal force than do lower threshold motor units. It has been hypothesized[73] that the lower firing rates observed in high threshold motor units may be due to their greater fatigability compared to low threshold motor units (Figure 11). Therefore, theoretically, the neuromuscular system activates high threshold motor units at lower firing rates to balance maximal force production with the duration that the force can be sustained.

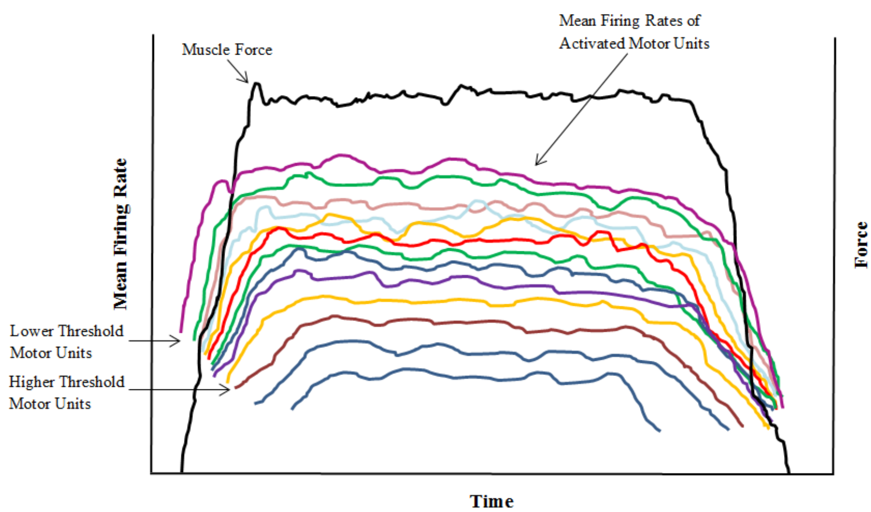

Figure 11. Representation of the Onion Skin Scheme.

Enoka and Stuart[77] suggested that delineating the differences between motor unit activation strategies may allow for identification of the mechanisms that result in task failure. In the current study, three motor unit activation strategies (AHP, Muscle Wisdom, and Onion Skin Scheme) are being considered, however, each have limitations[70,78,79]. For example, Fuglevand and Keen[78] suggested that Muscle Wisdom may not be an overall activation strategy during fatigue and that decreases in the frequency of stimulations may not optimize the duration of a fatiguing muscle action. In addition, De Luca and Contessa[70] suggested that the AHP theory does not always explain the process of fatigue because there is often, but not always, a decrease in firing rate. These studies used either stimulation[78] or simulation[70] models which have their own limitations and, therefore, no one theory can be disregarded based on stimulation or simulation studies alone. In addition, Barry and Enoka[80] have suggested that the motor unit activation strategies used during a fatiguing task may be intensity-, mode-, and muscle-specific. Therefore, the current study applied three commonly used motor unit activation strategies (AHP[71], Muscle Wisdom[69], and Onion Skin Scheme[73]) to identify the mechanisms that maintain force production at different time-points during the time course of fatigue-induced changes in the neuromuscular responses from DCER leg extension muscle actions to failure.

5.5 Strategies of the Quadriceps Femoris during the 30% 1-RM Protocol

The neuromuscular responses from the VL, VM, and RF for the 30% 1-RM protocol suggested that during the first 30% of the repetitions to failure, force production was primarily maintained by increases in muscle activation (EMG RMS) and motor unit recruitment (MMG RMS), without a significant contribution from rate coding (MMG MPF). These fatigue-related neuromuscular responses were not consistent with the AHP theory[71] which predicts an increase in firing rate and, therefore MMG MPF, to accompany the recruitment of higher threshold motor units during this early phase of the fatigue process. In the present study, however, the regression analysis indicated a decreasing pattern for MMG MPF throughout the fatiguing workbout that became significant at 30% of the repetitions to failure (Figure 4, 5, and 6). Both Muscle

Wisdom[69] and the Onion Skin Scheme[73] predict fatigue-related increases in muscle activation and motor unit recruitment, but decreases in the global motor unit firing rate and, therefore MMG MPF, during the 30% 1-RM protocol to failure. Thus, during the initial 30% of the fatigue process, either Muscle Wisdom or the Onion Skin Scheme could explain the neuromuscular responses to the 30% 1-RM protocol. According to Muscle Wisdom and the Onion Skin Scheme, the increases in EMG RMS and MMG RMS were likely due to motor unit recruitment. According to Muscle Wisdom[69], however, the decrease in MMG MPF was due to a central nervous system strategy designed to decrease motor unit firing rate, cause elongation of the twitch response, greater fusion of motor unit twitches to optimize force production, and delay the process of fatigue. The Onion Skin Scheme[73] hypothesizes that the decrease in motor unit firing rate, as reflected in the MMG MPF responses, was due to later recruited motor units having lower firing rates than the initially recruited motor units.

From 30 to 60% of the repetitions to failure during the 30% 1-RM protocol there were muscle-specific differences in neuromuscular responses. For the VL and VM there were no changes in global motor unit firing rate as evidence by the MMG MPF responses, but there was a decrease in MMG MPF for the RF. All three muscles, however, exhibited increases in muscle activation (EMG RMS), but a decrease in MMG RMS. The MMG RMS responses (Figure 4, 5, and 6) from the VL, VM, and RF suggested that increases in intramuscular fluid pressure (which decreases MMG RMS) had greater effects on the MMG signal then did motor unit recruitment (which increases MMG RMS) from 30 to 60% of the repetitions to failure[81]. In addition, the decrease in MMG MPF from the RF, but not the VL and VM, suggested a fatigue-related, muscle-specific, difference during the middle phase of low-intensity (30% 1-RM) DCER leg extension muscle actions to failure. Specifically, the RF demonstrated an earlier decrease in global motor unit firing rate (MMG MPF) than the VL and VM. Hu et al.[82] suggested that these muscle-specific differences may be explained by differences in muscle architecture with the RF being a bi-pennate architecture and a bi-articulate structure, while the VL and VM are uni-pennate and uni-articulate muscles[82,83]. In addition, Hu et al.[82] suggested that the RF was more fatigable than the VL and VM due to a greater type II fiber ratio. In the current study, the decrease in global motor unit firing rate, as reflected by MMG MPF, could not be explained by the AHP theory[71] which would suggest an increase in firing rate during a fatiguing workbout. Therefore, like the first 30% of the repetitions to failure, the AHP theory[71] was unable to explain the changes in neuromuscular responses from 30 to 60% of the repetitions to failure. Like the first 30% of the repetitions to failure, Muscle Wisdom[69] and the Onion Skin Scheme[73] may explain the neuromuscular responses from 30 to 60% of the repetitions to failure. Muscle Wisdom[69] suggests that the continued decrease in firing rate is a result of greater elongation of the twitch response, however, the Onion Skin Scheme[73] suggests that the greater decrease in firing rate is from newly recruited motor units having progressively slower firing rates. Thus, unlike the first 30% of the repetitions to failure, there were muscle-specific (VL and VM versus RF) differences in neuromuscular responses.

The neuromuscular responses from the VL, VM, and RF for the 30% 1-RM protocol suggested that from 60 to 100% of the repetitions to failure, force production was maintained by increases in muscle activation (EMG RMS) and motor unit recruitment (MMG RMS), but a decrease in global motor unit firing rate (MMG MPF).

In addition, all three muscles exhibited decreases in MUAP CV which were reflected in EMG MPF (Figure 4, 5, and 6). Unlike 30 to 60% of the repetitions to failure, there was an increase in MMG RMS which suggested that the increases in recruitment (which increases MMG RMS) overcame the effects of intramuscular fluid pressure (which decreases MMG RMS) on the MMG signal[67,81]. In addition, the decrease in EMG MPF suggested a fatigue-related buildup of metabolic byproducts that slowed MUAP CV and further supported the fatiguing nature of the workbout[48,57]. The increases in muscle activation and motor unit recruited accompanied by decreases in global motor unit firing rate during the fatiguing workbout may be explained by the AHP theory[71], Muscle Wisdom[69], or the Onion Skin Scheme[73]. The AHP theory[71] suggests that during the initial phases of a fatiguing workbout there are increases in recruitment and firing rate, however, as the process of fatigue continues there is a buildup of metabolic byproducts which slows MUAP CV and also results in decreases in firing rates. Muscle Wisdom[69] suggests that a continued increase in recruitment, greater muscle relaxation times, and decreases in motor unit firing rate optimize force production. The Onion Skin Scheme[73], however, suggests a continued increase in recruitment during the fatiguing process and that these newly recruited motor units have slower firing rates than previously recruited motor units. Therefore, the AHP theory[71], Muscle Wisdom[69], and the Onion Skin Scheme[73] could each explain the neuromuscular responses during the final phase (60 to 100% of the repetitions to failure) of the 30% 1-RM protocol.

5.6 Strategies of the Quadriceps Femoris during the 70% 1-RM Protocol

During the 70% 1-RM protocol, there were increases in EMG RMS and MMG RMS, but decreases in MMG MPF from the VL, VM, and RF (Figure 7, 8, and 9).

Specifically, the regression analyses indicated increases in EMG RMS and MMG RMS throughout the fatiguing workbout that became significantly greater than the initial repetition at 10, 20, and 10% of the repetitions to failure for the VL, VM, and RF, respectively. The regression analyses for MMG MPF from the VL, VM, and RF, however, indicated decreasing patterns throughout the fatiguing workbout that became significant at 10, 20, 70% of the repetitions to failure, respectively. Unlike the 30% 1-RM protocol, the neuromuscular responses from the 70% 1-RM protocol were the same for all three muscles throughout the fatiguing workbout. The neuromuscular responses during the 70% 1-RM protocol were not consistent with the AHP theroy[71], which would predict increases in motor unit firing rate (MMG MPF) during the initial phases of a fatiguing workbout. The increases in MMG RMS and decreases in MMG MPF could be explained by both Muscle Wisdom[69] and the Onion Skin Scheme[73] which would predict fatigue-induced increases in motor unit recruitment, but decreases in firing rate. The mechanisms underlying the expected decrease in motor unit firing rate, as reflected by MMG MPF, however, differ between Muscle Wisdom[69] and the Onion Skin Scheme[73]. Muscle Wisdom[69] suggests that the central nervous system employs a specific activation strategy that includes decreases in motor unit firing rate to maintain force production during fatigue. The Onion Skin Scheme, however, suggests a natural reserve of motor units and that earlier recruited motor units are firing at greater rates than later recruited ones.

In the current study, the 30% 1-RM protocol had three unique phases (1 to 30, 30 to 60, and 60 to 100% of the repetitions to failure) of neuromuscular responses and the 70% 1-RM protocol had only one (1 to 100% of the repetitions to failure). The neuromuscular responses were similar during the first 30% of the repetitions to failure from the VL, VM, and RF during the 30 and 70% 1-RM protocols, which exhibited increases in EMG RMS and MMG RMS, but decreases in MMG MPF. From 30 to 60% of the repetitions to failure there were decreases in MMG RMS during the 30% 1-RM protocol, but increases during the 70% 1-RM protocol. These findings suggested that low-load (30% 1-RM) CON-only DCER leg extensions are affected by greater intramuscular fluid pressure than high-load (70% 1-RM). This difference in intramuscular fluid pressure may be due to the greater total volume of work performed during the low-load (30% 1-RM) compared to the high-load (70% 1-RM) (Table 1)[7,81]. The last 40% of the repetitions to failure for the 30 and 70% 1-RM protocols exhibited increases in EMG RMS and MMG RMS, but decreases in MMG MPF. Together, these findings indicated an intensity-specific (30 versus 70% 1-RM) difference in neuromuscular responses during CON-only DCER leg extension muscle actions to failure. In addition to the differences in neuromuscular responses, three commonly used motor unit activation strategies (AHP theory[71], Muscle Wisdom[69], and the Onion Skin Scheme[73]) were used to compare the differences in the strategies used to maintain force production during low-load (30% 1-RM) and high-load (70% 1-RM) CON-only DCER leg extension muscle actions. The AHP theory was able to explain the neuromuscular responses from the final phase (60 to 100% of the repetitions to failure) of the 30% 1-RM protocol, but none of the phases from the 70% 1-RM protocol. Muscle Wisdom and the Onion Skin Scheme, however, were able to explain all phases of neuromuscular responses during both the 30 and 70% 1-RM protocols. Therefore, the findings of the current study suggested intensity- (30 versus 70% 1-RM) and muscle-specific (RF versus VL and VM) differences in the neuromuscular responses and that Muscle Wisdom[69] or the Onion Skin Scheme[73] better explained the maintenance of force than the AHP theory[71].

During the 30 and 70% 1-RM protocols, there were increases in EMG RMS and MMG RMS, decreases in EMG MPF and MMG MPF, but differences in the time-points at which these neuromuscular parameters changed. During the 30% 1-RM protocol, EMG MPF began to decrease earlier and decreased to a greater extent than during the 70% 1-RM protocol. This intensity-related (30 versus 70% 1-RM) difference in EMG MPF suggested a greater buildup of metabolic byproducts during the 30% 1-RM protocol compared to the 70% 1-RM protocol, which was likely related to the total amount of work performed. The increases in muscle activation (EMG RMS) and motor unit recruitment (MMG RMS) began at the initiation of the fatiguing workbouts for both protocols, however, the time course of changes in motor unit firing rate (MMG MPF) differed. The decrease in global motor unit firing rate, as reflected in MMG MPF, from the VL and VM occurred later in the 30% 1-RM protocol compared to the 70% 1-RM protocol. The decrease in firing rate from the RF, however, occurred earlier during the 30% 1-RM protocol than the 70% 1-RM protocol. These findings suggested intensity- (30 versus 70% 1-RM) and muscle-specific (RF versus VL and VM) differences in the time course of changes of global motor unit firing rate (MMG MPF). In addition, during the 70% 1-RM protocol, the later decrease in firing rate from the RF compared to the VL and VM may have been due to differences in muscle architecture, structure, and fiber type ratios[82,83]. The maintenance of force production, however, during both the 30 and 70% 1-RM protocols was primarily a result of increases in motor unit recruitment (MMG RMS). In addition, these findings suggested that the neuromuscular responses during both the 30 and 70% 1-RM protocols could be explained by Muscle Wisdom[69] or the Onion Skin Scheme[73], but not the AHP theory[71]. Thus, the general patterns of neuromuscular responses were similar for both protocols, however, the time course of changes were different.

5.7 *Summary*

There were decreases in pretest to posttest 1-RM and MVIC force after both the 30 and 70% 1-RM protocols. Furthermore, all three muscles exhibited the same neuromuscular responses for the 30 and 70% 1-RM protocols during both the 1-RM and MVIC measurements. During the 1-RM measurements, there were decreases in EMG MPF, and no changes in EMG RMS or MMG RMS after the 30 and 70% 1-RM protocols. In addition, there were decreases in MMG MPF after the 70% 1-RM protocol, but not the 30% 1-RM protocol. These neuromuscular responses suggested that there were decreases in MUAP CV (EMG MPF) during the 1-RM measurements for all muscles after both the 30 and 70% 1-RM protocols, but decreases in global motor unit firing rate (MMG MPF) after the 70% 1-RM protocol only. During the MVIC measurements, there were increases in MMG RMS, no change in EMG RMS, and decreases in MMG MPF and EMG MPF after both the 30 and 70% 1-RM protocols. These neuromuscular responses suggested increases in motor unit recruitment (MMG RMS), and decreases in MUAP CV (EMG MPF) and global motor unit firing rate (MMG MPF) during the MVIC measurements after the 30 and 70% 1-RM protocols. Therefore, there were mode- and intensity-specific, but no muscle-specific pretest to posttest neuromuscular responses after the DCER leg extension muscle actions to failure during the 1-RM and MVIC measurements.

There were three unique phases of neuromuscular responses during the 30% 1-RM protocol, but only one phase during the 70% 1-RM protocol. During the initial phase (1 to 30% of the repetitions to failure) of the 30% 1-RM protocol there were increases in EMG RMS and MMG RMS, but decreases in MMG MPF. The second phase (30 to 60% of the repetitions to failure), however, exhibited decreases in MMG RMS and MMG MPF, but increases in EMG RMS. The final phase (60 to 100% of the repetitions to failure) of the 30% 1-RM protocol exhibited increases in EMG RMS and MMG RMS, but decreases in EMG MPF and MMG MPF. The 70% 1-RM protocol resulted in increases in EMG RMS and MMG RMS, but decreases in EMG MPF and MMG MPF throughout the fatiguing DCER workbout. Thus, the neuromuscular responses during both the 30 and 70% 1-RM protocols suggested increases in muscle activation (EMG RMS) and motor unit recruitment (MMG RMS), but decreases in global motor unit firing rate (MMG MPF) and MUAP CV (EMG MPF). The time-points at which MMG MPF became significantly less than the initial repetitions, however, were later for the VL and VM than the RF during the 30% 1-RM protocol compared to the 70% 1-RM protocol. These time course of changes in neuromuscular responses during the 30 and 70% 1-RM protocols could both be explained by Muscle Wisdom[69] and the Onion Skin Scheme[73], but not the AHP theory[71]. The findings of the current study suggested that the time course of changes in neuromuscular responses can provide insight into muscle- and intensity-specific differences in the motor unit activation strategies used to maintain force production and allow for a greater understanding of the fatiguing process by identifying the time-points at which these neuromuscular parameters changed.

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