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The study of voluntary activation and force production relationships and responses to varied isometric strength training parameters during fatiguing and non-fatiguing test protocols

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THE STUDY OF VOLUNTARY ACTIVATION AND FORCE PRODUCTION RELATIONSHIPS AND RESPONSES TO VARIED ISOMETRIC STRENGTH TRAINING PARAMETERS DURING FATIGUING AND NON-FATIGUING TEST PROTOCOLS

by

David Monte Williams

An Abstract

Of a thesis submitted in partial fulfillment
of the requirements for the Doctor of
Philosophy degree in Physical Rehabilitation Science
in the Graduate College of
The University of Iowa

May 2011

Thesis Supervisor: Associate Professor H. John Yack

ABSTRACT

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The second training study investigated the effects of high resistance ramp versus ballistic type MVIC strength training of the quadriceps femoris on central adaptations in submaximal and maximal levels of MVIC VA and force production. Results showed similar ramp and ballistic group training increases in MVIC force and VA on both ramp

and ballistic tests. Ballistic group, ballistic test change scores were significant but not for the ramp test, suggesting ballistic group test-training specificity. The ballistic group showed significant force increases on the submaximal 150ms ballistic test, while the ramp group showed non-significant training changes, further supporting test-training specificity for the ballistic group.

Results support utility of the ITT and provide valuable information with regard to training and test-training specificity considerations.

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The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph.D. thesis of

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has been approved by the Examining Committee
for the thesis requirement for the Doctor of Philosophy
degree in Physical Rehabilitation Science at the May 2011 graduation.

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David H. Nielsen

To my mother Dixie Lee Bower, your love and support through the years has gotten me to where I am today. You taught me all I needed to know when I was a child to complete this degree: “life won’t always be fair, just bite your cheek, curl your toes under, and move on”

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To my children, Hannah and Hunter, thanks for always understanding when dad had to work late at the lab! As you grow and come across difficult challenges I hope watching me go through this process will help you to realize that nothing in life that is worthwhile is ever easy! Be persistent and follow your dreams!

Persistence.
Nothing in the world can take the place of persistence.
Talent will not;
nothing is more common than unsuccessful men with talent.
Genius will not;
unrewarded genius is almost a proverb.
Education will not;
the world is full of educated derelicts.
Persistence and determination alone are omnipotent.
Calvin Coolige

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CHAPTER 1

INTRODUCTION

Background of the Study

The ability of humans to produce muscle force has been studied extensively through the years, showing that the production of muscle force is dependent on the interaction of both central and peripheral mechanisms. Plasticity in these mechanisms has been demonstrated by the adaptation of force output secondary to the effects of injury, disease, fatigue, ageing, and training. The identification of the specific contribution of both central and peripheral mechanisms to muscle force production and the extent of their plasticity is a fundamental process in the development of intervention strategies to improve muscle force production. The interpolated twitch technique (ITT) has been used extensively to evaluate central mechanisms of muscle force production and their adaptation to injury, disease, fatigue, ageing, and training. Use of the ITT to assess central mechanisms is appropriate only if the technique demonstrates a certain degree of validity and it is used appropriately. In this case, the ITT could be utilized as an outcome measure for the effect of training on central mechanisms of muscle force production.

The Interpolated Twitch Technique (ITT) and its Development

Muscle force output is commonly measured in studies examining the effect of fatigue, resistance training, ageing, and injury on muscle function. Muscle force production is dependent on the intricate interaction of both central and peripheral physiologic mechanisms. Central mechanisms have been classified as those lying proximal to the alpha-motoneuron in the ventral horn of the spinal cord, while peripheral mechanisms are those lying distal to the alpha motoneuron (Gandevia 2001). Measures of peripheral adaptations to fatigue, resistance training, ageing, and injury are prolific in number and have been successfully used to delineate the changes that each of these

modalities produce. The development of methods to measure the contribution of central mechanisms to muscle force production has largely centered on the interpolated twitch technique (ITT) or one of its variations. Prior to the development of the ITT a number of researchers proposed the importance of central mechanisms in muscle force production and attempted to quantify it. In his works examining the contribution of central and peripheral physiologic mechanisms in the development of muscular fatigue, Alessandro Mosso, utilized crude electrical stimulation to compare voluntarily produced force output with electrically elicited force output, and also demonstrated that excessive mental "work" could decrease force output of the finger flexors, thus implicating central mechanisms in the development of muscle fatigue (Mosso 1904). Waller, Lombard, and others demonstrated that at times muscular excitability was preserved after voluntary task failure secondary to the fact that electrical stimulation of the nerve or muscle would still elicit muscular force, once again implicating inadequate central mechanisms (Waller 1891; Lombard 1892; Reid 1928). A common view developed that maximal contractile force was so high that "strength is kept in bounds by the inability of the higher centers to activate the muscles to the full," in effect protecting the muscles, tendons, and bones from injury (Merton 1950).

The production of muscle force is regulated through two mechanisms of motor unit control, motor unit recruitment and rate coding (Duchateau, Semmler et al. 2006), which are not mutually exclusive. Recruitment is the process by which the order of motor unit activity is regulated. At low levels of voluntary force, slow contracting motor units that produce low levels of tension are recruited, and as the level of voluntary force increases faster motor units with higher tensions are recruited. This has come to be known as the size principle of motor unit recruitment and was originally described by Henneman and colleagues (Henneman, Somjen et al. 1965). The mechanism underlying this process of orderly recruitment has been based in large part on Ohm's Law which states E = IR, where E is the excitatory synaptic potential, I is the synaptic current, and R

is the input resistance of the neuron. An inverse relationship exists between a neuron's surface area and its input resistance in that the smaller the neuron, the larger its passive input resistance. Therefore, for a given level of synaptic current a larger synaptic potential will be produced in a smaller neuron than in larger neuron (Kandel ER 1991; Duchateau, Semmler et al. 2006). The amount of force produced by muscle contraction can also be varied by modulating the rate of firing of motor neurons (Duchateau, Semmler et al. 2006). This has come to be known as rate coding. Force increases as motor neuron firing frequency increases secondary to the fact that successive twitches can summate. Under normal conditions of muscle contraction firing rates stay within a relatively narrow range, ranging from a low frequency of 5-8 Hz (Sogaard, Christensen et al. 1996; Van Cutsem, Feiereisen et al. 1997) to a high frequency of approximately 30-50 Hz (Enoka and Fuglevand 2001) during isometric contractions. These firing rates produce unfused tetanus; higher rates of firing that would produce fused tetanus occur only briefly during the early phase of rapid contractions (Kandel ER 1991). As one considers developing a technique to measure the completeness of muscle activation by the central nervous system (CNS), it would appear that superimposing supramaximal electrical stimulation on an ongoing contraction would be a viable method. It would be expected that when supramaximal electrical stimulation is applied to the nerve trunk or intramuscular nerve branches during a voluntary contraction, the motor units that have not already been recruited, would create a twitch response in force (Belanger and McComas 1981). By the same rationale, those motor units that have been recruited but are not firing at an optimal rate and whose motoneurones are not in a refractory state would create a twitch response in force (Belanger and McComas 1981). As one drives their muscles more completely in a voluntary manner progressively more motor units are recruited and are firing at their optimal level, therefore the superimposed twitch becomes smaller and eventually disappears. At the point where superimposed stimulation no longer produces an increment of force, it can be inferred that VA is complete. In 1928,

Denny-Brown demonstrated this progressive occlusion of force produced by electrical stimulation superimposed on voluntary contractions as the intensity of the voluntary contractions progressively increased (Denny-Brown 1928). Merton then used the interpolated twitch to study the completeness of muscle activation in 1954 (Merton 1954). He studied the adductor pollicis, and found a negative linear relationship between ulnar nerve elicited twitch force and voluntary isometric thumb adduction force, and noted no evidence of an interpolated twitch during maximum voluntary contractions. He therefore concluded that the adductor pollicis could be fully activated by the CNS. Work by a number of other investigators reported the same finding, that the majority of healthy subjects could fully activate the majority of the muscles that were studied with the interpolated twitch technique (Belanger and McComas 1981; Bigland-Ritchie, Furbush et al. 1986; Rutherford, Greig et al. 1986; Rutherford, Jones et al. 1986; Davies J 1988; Garfinkel and Cafarelli 1992). However, since these early studies, more sensitive techniques with higher resolution have been developed and studies utilizing these advances suggest that complete VA is not as pervasive as previously reported (McKenzie, Bigland-Ritchie et al. 1992; Allen, Gandevia et al. 1995; Gandevia, Allen et al. 1996; Herbert and Gandevia 1996; Allen, McKenzie et al. 1998; Jakobi and Cafarelli 1998; Roos, Rice et al. 1999; Babault 2002; Behm, Whittle et al. 2002; Williams, Sharma et al. 2002; Williams and Bilodeau 2004). A thorough understanding of the technical modifications, application techniques, and analysis system requirements for the ITT is required to ensure the proper application of the technique.

In summary, it has been understood for years that both central and peripheral physiologic mechanisms contribute to the production of muscle force. Very early researchers utilized crude electrical stimulation and force measurement systems to demonstrate that central mechanisms could be impaired with active contractions and through mentally taxing activities, such as delivering professional lectures. Then in the mid 1950's with the development of the ITT it was demonstrated that most subjects were

able to fully drive most of the muscles that were investigated using this technique. However, these early ITT studies lacked the sensitivity and resolution needed to display the small forces interpolated on the ongoing force of a maximum voluntary contraction. More recent studies utilizing sensitive force measurement systems and supramaximal electrical stimulation, to ensure complete motor unit recruitment and maximal firing frequency, have demonstrated that subjects typically cannot achieve 100% VA. A thorough understanding of the technical and applied limitations of the ITT is necessary to allow accurate interpretation of its body of literature, and to plan a study utilizing the technique. These technical and applied limitations are the focus of the next section.

Validation of the Interpolated Twitch Technique and Its Limitations

Merton (Merton 1954) initially described a negative linear relationship between the interpolated force and voluntary force when using the ITT and this was corroborated by other investigators (Chapman SJ 1985; Gandevia and McKenzie 1988). A linear relationship implies that the level of VA can be quantified with the linear equation: VA (%) = [1-(interpolated evoked twitch/control evoked twitch)] x 100, and that the muscle's true maximal force can be determined from a single interpolated twitch ratio (Shield and Zhou 2004). However, other investigators have found the interpolated force to voluntary force relationship to be non-linear at medium to high force levels (Belanger and McComas 1981; Dowling, Konert et al. 1994; Behm, St-Pierre et al. 1996; Suter E 1996). Lack of a linear relationship between interpolated and voluntary force brings into questions the validity of the technique, however, the relationship could be non-linear for a number of reasons other than a non-linearity in the relationship between activation of the stimulated muscle and evoked forces (Shield and Zhou 2004). Potential limitations of the ITT which could contribute to the non-linearity of the interpolated and voluntary force relationship can largely be divided into five groups: 1) mechanical limitations,

2) physiologic limitations, 3) technical/practical limitations, 4) subject limitations, and 5) limitations in the quantification of VA. Each of these limitations is individually addressed in the following sections with recommendations from the literature to minimize them.

Mechanical Limitations

The first of the mechanical limitations is the possibility that unstimulated synergists contribute to the net force of the contraction (Behm, St-Pierre et al. 1996; Allen, McKenzie et al. 1998; Williams and Bilodeau 2004). This limitation is present in most muscle preparations present in the body. In the case where percutaneous stimulation is applied to the gastrocnemius/soleus complex (ankle plantar flexors), unstimulated peroneal muscles (ankle plantar flexors and evertors), could contribute to the overall plantar flexion force development during a voluntary contraction, but would not necessarily be stimulated. When percutaneous stimulation is applied to the biceps brachii, the unstimulated brachialis, brachioradialis, and extensor carpi radialis brevis could all contribute to the overall elbow flexion force. Allen and colleagues (Allen, McKenzie et al. 1998) assessed the level of VA at high elbow flexion force levels of the radially innervated brachioradialis and the biceps brachii innervated by the musculocutaneous nerve. They demonstrated a significantly lower level of VA for the brachioradialis 91.5% versus the biceps brachii 99.1% and this lends support to the hypothesis that elbow flexor synergists other than the biceps brachii may contribute extra force at high voluntary torques. This contribution of synergist elbow flexors exemplifies the limitation of the technique to assess VA of the elbow flexors as a group. However, the technique will yield a valid measure of the level of VA of the stimulated muscles if VA is expressed as the proportion of the response evoked by the stimulus during voluntary efforts to the response evoked by the same stimulus in the relaxed muscle (Allen, McKenzie et al. 1998). Percutaneous stimulation though optimal in this case does

have its own limitations such as the potential for activation of antagonist muscles, and secondary to the fact that it may not activate the same proportion of the muscle from session to session. Ideally one would find a muscle preparation in which synergist contribution to muscle force production would be minimal. Such preparations exist with the quadriceps and first dorsal interossei. However, in these muscle groups the type of stimulation applied must be considered carefully. Stimulation of the nerve trunk in the case of the femoral nerve for the quadriceps would also cause contraction of the sartorius, a knee flexor, and in this case antagonist activity could limit net force production. Likewise, in the case of ulnar nerve stimulation activation of the second palmar interossei, an adductor, would negate force produced by the first dorsal interossei, an abductor. Therefore, in both of these muscle preparations, percutaneous stimulation of the muscle belly represents a better option to minimize force cancellation by antagonist activation. The remainder of the mechanical limitations deal with changes in length of the muscle as a whole or of the series elastic component of the contractile mechanism. "Static" voluntary contractions are rarely isometric secondary to any of the following factors: 1) tendon stretch, 2) movement of other body parts involved in stabilization of the joint under study, and/or 3) compliance within the joint (Allen, McKenzie et al. 1998). James, et al. examined several different methods for measuring the force-velocity relationship of the quadriceps femoris in humans and noted that with high force voluntary quadriceps contractions with the knee flexed, despite "assiduous strapping" of the subject, it was difficult to eliminate extension of the hip during contraction (James, Sacco et al. 1994). The authors explain that this hip extension would: 1) lengthen the rectus femoris moving it closer to its optimal length for contraction and 2) place a passive stretch on the rectus femoris thereby increasing the measured force. Allen and colleagues investigated the effect of changes in muscle length on measurement of VA in the biceps brachii, and found that the majority of elbow flexion maximum voluntary isometric contraction (MVIC) trials (95%) were accompanied by a small amount of shortening of

the elbow flexors (elbow flexion) at the initiation of contraction (Allen, McKenzie et al. 1998). Loring and colleagues utilized either a more compliant (rubber tubing) or less compliant (steel cable) coupling device in their measurement of thumb adduction force and demonstrated at all levels of voluntary contraction that the displacement of the thumb was greater and the interpolated twitch force was less for the more compliant link (Loring and Hershenson 1992). There are many source of nonlinearity in the force measurement system such as the give in the seat and back support, the resistance pad, the stabilizing straps, or any other moveable articulation in the measurement system. Bulow et al.in 1993 (Bulow, Norregaard et al. 1993) studied the effect of changes in muscle length, stimulation intensity, potentiation, and force level on the interpolated twitch to ongoing force relationship. They demonstrated that the interpolated twitch size increased with greater levels of potentiation, reaching a plateau for potentiating contractions of 70-80% of MVIC. From 0 to approximately 20-25% of MVIC twitch size increased in size, but beyond that force level there was a linear decrease in twitch size with increasing force. Reducing the amplitude of the stimulation made the relationship between interpolated force and voluntary force become less linear. This is most likely due to the loss of force when the force from the stimulated portion of the muscle is transmitted through the nonstimulated portion of the muscle. When muscle length was reduced (the knee was moved from 90° to 70° of flexion) the effect was the same as when the amplitude of the stimulation was decreased in that the interpolated force to voluntary force relationship became less linear. Increasing the muscle preload (by changing the hip angle from 90° of flexion to 0° of flexion, thereby lengthening the rectus femoris) altered the relationship between interpolated twitch and voluntary force at force levels below 25% of maximum by increasing the size of the interpolated twitches (Bulow, Norregaard et al. 1993). Researchers can put the information gleaned from these studies to use in an effort to minimize the deleterious effects of system compliance on the interpolated force to voluntary force relationship. Researchers should ensure that their measurement system is

as non-compliant as possible by using rigid strapping/stabilization materials to secure the subject, ensuring solid fixation of the limb to the force measurement transducer, preloading the point of juncture between the subject and the force measurement system, and ensuring that compliance in the force measurement system is minimized. Testing at MVIC will maximize the potential for the entire muscle to be activated therefore minimizing the possibility of force loss secondary to its transmission through the non activated portion of the muscle (Bulow, Norregaard et al. 1993), and if testing at force levels less than 100% MVIC testing the muscle in a lengthened position will help to minimize force loss by preloading the musculotendinous unit with stretch (Bulow, Norregaard et al. 1993). Furthermore, optimizing stimulation parameters by using multiple stimuli (doublet or train) versus single pulses and delivering them at a supramaximal level will minimize force loss secondary to a greater percentage of the muscle being activated (Miller, Downham et al. 1999). As the muscle approaches maximal contraction, slack within the series elastic component of the muscle and within the force measurement system is taken up and the system becomes less compliant (Loring and Hershenson 1992; Suter and Herzog 2001).

Physiologic Limitations

Physiologic limitations can also pose a threat to the relationship between evoked and voluntary force. When stimulation is superimposed on an ongoing contraction, action potentials that travel in both an orthodromic and antidromic manner are produced in nonrefractory motor and sensory axons (Herbert and Gandevia 1999). Orthodromic conducting action potentials on a motor axon produce a nearly synchronous twitch in muscle force, whereas antidromic conducting action potentials on a motor axon can decrease the twitch in muscle force, even at short latencies, because of their collision with voluntarily produced orthodromic action potentials (Herbert and Gandevia 1999). This collision of electrically elicited antidromic action potentials and voluntarily produced

orthodromic action potentials leads to a reduction in the net rate of motoneuron discharge immediately after the application of the electrical stimulation secondary to cancellation of voluntary orthodromic action potentials from the motor neuron by the electrically elicited antidromic action potentials. This cancellation leads to a reduction in the size of the elicited twitch. Some of the electrically elicited antidromic action potentials will reach the motoneuron soma and produce hyperpolarization and may travel along recurrent nerve branches reaching Renshaw cells, evoking inhibitory postsynaptic potentials in motoneurons (Herbert and Gandevia 1999). The orthodromically and antidromically conducting action potentials on the sensory axons produced by the electrical stimulation can also influence motoneuron discharge after stimulation secondary to short and longer-latency reflex effects (Herbert and Gandevia 1999). Herbert and Gandevia created a computer model of the human adductor pollicis motoneuron pool and examined the effect of this collision of antidromically conducting electrically elicited action potentials on voluntary orthodromically conducting action potentials. They demonstrated in their model that the antidromically conducting action potentials had their greatest effect when the level of voluntary contraction was between 40 and 80% of maximum. With voluntary contractions less than 40% of maximum the superimposed response is only slightly influenced because the majority of motor units that respond with an increase in force is much greater than the units that respond with a decrease in force. When the voluntary force level is greater than 80% of maximum the superimposed response is decreased to a small extent because the rising phase of the superimposed response is either already complete or nearly complete before the spinal influence of stimulation has had time to reduce the voluntary force (Herbert and Gandevia 1999). Therefore, VA will be only slightly overestimated when comparing superimposed twitches to control twitches in healthy subjects who are capable of relatively high (>85%) VA. From a physiologic standpoint it has also been suggested that twitch interpolation involving single superimposed stimuli may not be able to reveal sub-optimal motor unit firing rates

(Miller, Downham et al. 1999; Maffiuletti, Pensini et al. 2002), and that the evoked-voluntary force relationship becomes less steep, even non-linear, at force levels in which recruitment is complete and rate coding is the only means of increasing force (Scaglioni, Ferri et al. 2002). This potential physiologic limitation is disputed by research demonstrating that increased force output occurs when an extra stimulus is applied to a muscle or motor unit that is being stimulated at a sub-optimal rate (catch-like property of muscle) (Burke, Rudomin et al. 1970; Belanger and McComas 1981; Herbert and Gandevia 1999; Suter and Herzog 2001). This proposed limitation is further disputed by research examining the adductor pollicis, a muscle in which recruitment is almost complete at 50% of MVIC (Kukulka and Clamann 1981). In this muscle it would be expected that the evoked to voluntary force relationship would diverge sharply from a linear relationship at 50% of MVIC if complete recruitment fully occluded interpolated stimulation, and this has not been demonstrated in studies where a non-compliant force measurement system is utilized (Merton 1954; Loring and Hershenson 1992). Therefore, a single supramaximal stimulus will be able to detect sub-optimal firing rates if other technical considerations are followed, however, a single stimulus may not represent the optimal stimulation choice when studying central fatigue which will be discussed in the next section.

Technical and Practical Limitations

When considering technical limitations in the application of the ITT, the point of application of the interpolated electrical stimulation would be one of the first things to consider. If the stimulation also activates muscles which are antagonists to the muscle(s) under study the amplitude of the control twitches may be reduced and the amplitude of the interpolated twitches during a near maximal or maximal voluntary contraction may be completely eliminated. Electrical stimulation is generally applied through electrodes placed over the nerve trunk of the muscle(s) of interest or through electrodes placed over

the muscle belly of the muscle(s) of interest. Both methods of stimulation could inadvertently activate antagonist muscles. In the case of studies examining the quadriceps femoris or the tibialis anterior, nerve stimulation of the femoral nerve or common peroneal nerve, respectively, would be suboptimal due to the activation of the sartorius and peroneals, muscles which are antagonist to the quadriceps and tibialis anterior, respectively. Similarly, placing surface stimulating electrodes too close to antagonists, too far apart, or using excessively large stimulating electrodes could increase the likelihood of activating antagonists (Awiszus, Wahl et al. 1997; Burke and Gandevia 1998). If surface stimulation is utilized, electrodes should be placed close to the motor point of the muscle, and electromyography (EMG) can be utilized to monitor antagonist muscle for activity elicited by electrical stimulation.

When considering the intensity of electrical stimulation to use choosing submaximal stimulation intensity would be easy due to the fact that submaximal stimulation is more easily tolerated by subjects and it also lessens the likelihood of activating antagonist muscles. That being said, several reasons exist which lead the researcher to choose supramaximal stimulation. With submaximal stimulation different portions of the muscle may be stimulated with each successive stimuli applied (Behm, St-Pierre et al. 1996). Behm and colleagues (Behm, St-Pierre et al. 1996) demonstrated that the proportion of the quadriceps activated using submaximal femoral nerve stimulation was lower during maximal voluntary efforts than during rest. This was partially explained by the potential for the stimulating electrode to be moved by the contracting muscle. Supramaximal stimulation minimizes the effect of small movements of the electrode relative to the underlying muscle or nerve trunk increasing the likelihood that the same proportion of muscle is activated in both maximal and sub maximal contractions (Behm, St-Pierre et al. 1996). Studies examining the effect of fatigue on VA must also carefully consider the intensity of the stimulation used for the ITT. As fatigue develops, alterations in excitation-contraction coupling lead to the development of low frequency

fatigue (Vagg, Mogyoros et al. 1998). In this state, the evoked response will decrease to a greater extent for those elicited with single stimuli as compared to those elicited with multiple stimuli delivered at a high rate (Bigland-Ritchie, Furbush et al. 1986; McKenzie, Bigland-Ritchie et al. 1992).

Methods to maximize the sensitivity of the ITT have received a substantial amount of research attention. Any method that can increase the signal to noise ratio of the technique is valuable to the researcher secondary to the fact that as the level of VA increases the size of the interpolated twitch decreases and the variability in voluntary force increases thus decreasing the signal to noise ratio (Galganski, Fuglevand et al. 1993). Merton originally utilized the ITT by superimposing a single stimulus on the contracting muscle (Merton 1954). Since that time researchers have utilized doublets or trains of stimulation in an attempt to increase the signal to noise ratio (De Serres and Enoka 1998; Jakobi and Cafarelli 1998; Miller, Downham et al. 1999; Behm, Whittle et al. 2002; Williams, Sharma et al. 2002; Williams and Bilodeau 2004; Bilodeau 2006). It has been shown that the variability of the interpolated twitch torque progressively decreases as the number of interpolated stimuli increases from a single twitch, to a doublet, then triplet, and eventually a quadruplet stimulation of the quadriceps femoris (Suter and Herzog 2001). A number of other studies have also demonstrated that train stimulation more often evokes an interpolated twitch torque than a single twitch (Strojnik 1995; Kent-Braun and Le Blanc 1996; Miller, Downham et al. 1999). Also in studies examining the effect of fatigue on the level of VA, train stimulation should be utilized secondary to the fact that as the muscle fatigues changes in excitation-contraction coupling (low frequency fatigue) predicate that the interpolated twitch force will decline to a greater extent than the interpolated train force would (Bigland-Ritchie, Furbush et al. 1986; McKenzie, Bigland-Ritchie et al. 1992).

Resolution of the force measurement system represents another potential technical limitation. To detect a 1% deficit in activation, the force measurement system must be

able to resolve force increments that are 1% of the amplitude of the control twitches (Allen, McKenzie et al. 1998; Todd, Gorman et al. 2004). Therefore resolution of the force measurement system utilized in the study is of paramount importance and should be clearly stated in the study. Early ITT studies rarely stated the resolution of their measurement system and therefore their results are suspect. Hales and Gandevia developed a measurement system which removed the initial DC-offset associated with voluntary contractions and amplified the remaining superimposed signal (x10) without distorting it, thus ensuring their ability to measure very small increments of superimposed force (Hales and Gandevia 1988). Using this device they were able to demonstrate that subjects could voluntarily activate the diaphragm (Gandevia and McKenzie 1985; Gandevia and McKenzie 1988) and abductor digiti minimi, elbow flexors, and tibialis anterior (Gandevia and McKenzie 1988) to a level of 98-99% even when using single interpolated stimuli. In this study Hales and Gandevia suggest two methods to improve the resolution of the ITT: 1) utilization of a train of stimulation to elicit greater evoked responses and 2) averaging the force responses of interpolated stimuli that show no evidence of force increments. As previously stated, it has become common for researchers to utilize doublet (Behm, St-Pierre et al. 1996; Allen, McKenzie et al. 1998; Roos, Rice et al. 1999; Kawakami, Amemiya et al. 2000; Suter and Herzog 2001) or train stimulation (Allen, McKenzie et al. 1998; Miller, Downham et al. 1999; Suter and Herzog 2001; Williams, Sharma et al. 2002; Williams and Bilodeau 2004) as opposed to a single pulse (Merton 1954; Chapman SJ 1985; Bigland-Ritchie, Furbush et al. 1986; Davies J 1988; Garfinkel and Cafarelli 1992; Allen, McKenzie et al. 1998; Miller, Downham et al. 1999; Suter and Herzog 2001) in an attempt to increase the signal to noise ratio. Furthermore, researchers are predominantly using supramaximal stimulation. Maximizing the elicited force is critical as smaller activation deficits can be detected when the force elicited with control stimulation is larger for a given level of force resolution.

The timing of the application of the stimulation is the final technical consideration to be discussed. To ensure the most accurate measurement of the extent of VA one would want to apply the interpolated stimulation at the peak of the voluntarily produced force, however, this can be challenging secondary to the ever changing force output at maximal contraction. Two methods have been utilized in an attempt to maximize the chance that the interpolated stimulation is applied at the peak of voluntary force production. Some authors have chosen to trigger the interpolated electrical stimulation soon after the voluntary force reaches its peak (Allen, Gandevia et al. 1995). In this method the triggered interpolated stimulation is always delivered slightly after the peak force is achieved, therefore the researchers using this technique are always settling for measuring slightly less than complete activation. Researchers will often manually deliver the interpolated stimulation attempting to deliver it at the peak force level by visually observing the force trace of the ongoing contraction (Williams, Sharma et al. 2002; Williams and Bilodeau 2004; Bilodeau 2006). When using this technique researchers will generally deliver multiple stimuli during the ongoing contraction hoping that one of the superimposed stimuli is delivered at the peak force output. With this method the chance of delivering the interpolated stimulation at the peak force level is maintained.

Subject Limitations

Subjects bring with them several potential limitations to the application of the ITT, and these must be controlled in order to optimize technique application. Subjects who have not been familiarized to performing MVIC's and to superimposed stimulation display inconsistent MVICs, and commonly change their performance when interpolated stimulation is expected. Therefore the inclusion of a familiarization session allowing the subject to practice MVICs and to experience the superimposed stimulation that will be utilized in the study is imperative (Gandevia 2001). Similarly, subject motivation can alter force output with strength testing. It has been demonstrated that loud verbal

encouragement significantly enhances subject performance on exercise tests, with its greatest effects in untrained subjects (Moffatt, Chitwood et al. 1994; McNair, Depledge et al. 1996; Andreacci, LeMura et al. 2002). This encouragement should be consistent between subjects and testers (Gandevia 2001). Furthermore, providing the subjects with objective online feedback during the performance of the MVIC helps to optimize performance, and is commonly provided in a visual manner (Gandevia 2001). When performing MVIC testing even well motivated and familiarized subjects will have an "off" contraction, and rejection criteria should be established to allow subjects and researchers to reject these efforts (Gandevia 2001). Rejection criteria that have been outlined in the literature include: 1) subjects are allowed to reject any contraction that they do not perceive as "maximal," 2) the force record shows no obvious plateau before superimposed stimulation is applied, 3) the interpolated stimulation is given when the voluntary force is not at or very near its maximum for that particular contraction (Gandevia 2001; Shield and Zhou 2004). It has been recognized that some individuals even after ITT test familiarization still show abnormally low levels of VA. In order to screen out atypical candidates, a subject rejection criterion of less than 75% VA during ITT MVIC testing was adopted for this research.

Limitations In The Methods Of Expressing Voluntary Activation

The level of VA of the stimulated muscle is typically quantified with the linear equation: VA (%) = [1-(interpolated evoked twitch/control evoked twitch)] x 100 (Merton 1954). This equation assumes that the relationship between the evoked and voluntary force is linear, however this relationship has been shown to be non-linear primarily at high force levels (Belanger and McComas 1981; Behm, St-Pierre et al. 1996; Suter E 1996; Allen, McKenzie et al. 1998; Williams and Bilodeau 2004). However, the non-linearity in the evoked-voluntary force relationship could be the result of any of the

previously discussed limitations, and not necessarily due to a non-linear relationship between the evoked and voluntary force. An alternative method of expressing the level of VA is to express the MVIC force as a percentage of the total force produced during the interpolated response, with this value being termed the Central Activation Ratio (CAR) (Kent-Braun and Le Blanc 1996; Stackhouse, Dean et al. 2000). With this technique it is assumed that the interpolated stimulation along with the voluntary MVIC will elicit the muscle's true maximum force, however, this may not be the case. True MVIC force is usually determined by a number of synergists, however only the stimulated muscle creates the superimposed force increment. Therefore, in cases where unstimulated synergists would contribute to the total MVIC force the CAR will tend to report exaggerated levels of VA (Behm, Power et al. 2001; Bilodeau 2006). Use of the first equation of VA where the interpolated evoked twitch force is expressed as a percentage of the control evoked twitch force removes the concerns regarding unstimulated synergists and may represent a better expression of VA.

Implementing the ITT in a manner which optimally controls all of its potential limitations is the goal of any study examining the level of VA. A significant body of work exists which outlines the five main groupings of limitations of the ITT, and technical and applied methods are presented which help to minimize these potential limitations. It has been suggested that suboptimally activated synergists could explain the nonlinearity of the interpolated evoked twitch – voluntary torque relationship (Behm, St-Pierre et al. 1996). To this end, our first study (Chapter 2) examined if suboptimal activation of synergistic muscle would explain the nonlinear nature of the interpolated twitch-voluntary torque relationship in the elbow flexors.

Central Fatigue

As outlined in the previous section muscle force production is dependent on both central and peripheral mechanisms working harmoniously to create muscle contraction.

When a contraction is sustained for a period of time, a condition of fatigue is said to develop and muscle force production decreases. This decrease in force could be brought on by impairments of central and/or peripheral mechanisms of muscle force production. The ITT has been utilized extensively to examine the contribution of failure of the central mechanisms of muscle force production to the development of neuromuscular fatigue (Merton 1954; Newham, McCarthy et al. 1991; McKenzie, Bigland-Ritchie et al. 1992; Gandevia, Allen et al. 1996; Loscher, Cresswell et al. 1996; Kawakami, Amemiya et al. 2000; Williams, Sharma et al. 2002; Bilodeau 2006). Prior to discussing the contribution of central mechanisms to the development of fatigue several terms must first be defined. Muscle fatigue is defined as any exercise-induced reduction in the ability of a muscle to generate force or power; it has both central and peripheral causes (Gandevia 2001). Central fatigue is defined as a progressive reduction in VA of muscles during exercise, and peripheral fatigue is defined as fatigue produced by changes at or distal to the neuromuscular junction (Gandevia 2001). VA simply refers to the level of voluntary drive during a contraction and does not differentiate between drive to the motoneuron pool or drive to the muscle (Gandevia 2001).

In Merton's introductory study utilizing the ITT, a single pulse of interpolated stimulation was utilized to assess the level of VA in fatiguing contractions of the adductor pollicis. He demonstrated that the level of VA did not diminish as fatigue developed, thus placing the location of fatigue entirely in the peripheral structures (Merton 1954). However, the use of single interpolated stimuli on fatiguing contractions decreases the sensitivity of the technique secondary to the slowing of the contractile mechanism and the presence of low-frequency fatigue (Marsden 1969; Marsden, Meadows et al. 1971; Grimby, Hannerz et al. 1981; Bellemare, Woods et al. 1983; Bigland-Ritchie, Johansson et al. 1983; Marsden, Meadows et al. 1983). Studies utilizing multiple high-frequency stimuli superimposed on fatiguing contractions have demonstrated that the level of VA decreases as fatigue develops, thus demonstrating that

both central and peripheral failure can contribute to the development of muscle fatigue (Bigland-Ritchie, Furbush et al. 1986; Newham, McCarthy et al. 1991; McKenzie, Bigland-Ritchie et al. 1992; Gandevia, Allen et al. 1996; Herbert and Gandevia 1996; Loscher, Cresswell et al. 1996; Kent-Braun 1999; Kawakami, Amemiya et al. 2000; Bilodeau, Henderson et al. 2001; Williams, Sharma et al. 2002; Schillings, Hoefsloot et al. 2003; Nordlund, Thorstensson et al. 2004; Bilodeau 2006).

The contribution of central mechanisms of muscle force production to the development of fatigue has been shown to be variable from one muscle group to another and to be task dependent (McKenzie, Bigland-Ritchie et al. 1992; Williams, Sharma et al. 2002; Bilodeau 2006). McKenzie et al.(McKenzie, Bigland-Ritchie et al. 1992) utilized an intermittent fatigue protocol consisting of three sets of ten 10-second maximum contractions with 10-second rest periods between contractions (50% duty cycle) for elbow flexors and diaphragm expulsive maneuvers, along with three sets of ten, 3-second 50% MVIC of diaphragm expulsive maneuvers (60% duty cycle) to examine the effect of fatigue on VA of the elbow flexors and the diaphragm along with the differential effect of two different fatigue protocols (McKenzie, Bigland-Ritchie et al. 1992). In the fresh state, subjects demonstrated significantly greater VA of the elbow flexors (98.4%) as compared to the diaphragm (95%) ($p<0.05$). During the fatigue protocol, the VA of the elbow flexors declined significantly to a level of 86.8%, which is in contrast to the insignificant decline in VA of the diaphragm during inspiratory contractions to a level of 91.5% ($p>0.05$) when maximum contractions are used in the fatigue protocol. When sub maximal (50%) expulsive maneuvers were utilized to induce fatigue in the diaphragm the activation index for the diaphragm during expulsive maneuvers decreased significantly from 92% to 61%, which is in sharp contrast to the insignificant decrease in activation index for the diaphragm during inspiratory maneuvers from 97.5% to 94%. This study demonstrates both the varying degree of susceptibility to central fatigue of different muscle groups, and the task dependency of central fatigue as demonstrated by the

differential effect of sub maximal fatiguing contractions on inspiratory and expiratory maneuvers of the diaphragm. The susceptibility of individual muscles to central fatigue has also been demonstrated in a series of studies in which an identical fatigue task (sustained maximal contraction until torque fell below 50% of pre-fatigue maximum torque for 5 s) was utilized to fatigue the elbow flexors (Bilodeau, Erb et al. 2001; Williams, Sharma et al. 2002) and extensors (Bilodeau 2006). In these studies it was demonstrated that VA of the elbow extensors is decreased significantly at the end of the fatigue task (Bilodeau 2006), whereas no significant central fatigue has been discerned in the elbow flexors (Bilodeau, Erb et al. 2001; Williams, Sharma et al. 2002). In general these muscle and task dependent differences in the development of central fatigue follow nicely with simple reasoning. One would expect a muscle such as the diaphragm to be more resistant to central fatigue than the biceps brachii secondary to the frequency with which the diaphragm contracts throughout the day and to the implications that a fully fatigued diaphragm would present to survival of the subject. Furthermore the fact that a greater degree of fatigue was demonstrated with diaphragm expulsive maneuvers than with diaphragm inspiratory maneuvers follows the specificity of training/testing principles well, secondary to the fact that intermittent submaximal (50%) expulsive maneuvers were utilized to fatigue the diaphragm.

Studies suggest that low-force, long-duration contractions are more likely to lead to the development of central fatigue than high-force, short-duration contractions performed by the same muscle group (Behm and St-Pierre 1997; Bilodeau, Erb et al. 2001; Bilodeau, Henderson et al. 2001). Bilodeau conducted a study of the triceps brachii in which the effect of intermittent and continuous contraction on the degree of central fatigue was assessed using three different fatigue tasks with all contractions carried out at the level of an MVIC (Bilodeau 2006). VA of the triceps brachii was monitored before, during and after each of the three different fatigue tasks: 1) elbow extension MVIC held until force output decreased by 50% (short task), 2) 3-min

continuous elbow extension MVIC and 3) 3-min elbow extension MVIC with 5-s rest periods every 30-s. It was found that the 3-min continuous elbow extension MVIC contraction elicited a significant decrease in central activation beginning at the half-way point of the contraction and persisting for its duration as compared to the 3-min intermittent elbow extension MVIC contraction which did not create a significant decrease in VA until the end of the three minutes. The short fatigue task elicited a significant decrease in VA at the end of the task, that when compared to the same time-point in the three-minute fatigue tasks was similar.

The ability of the mechanisms of VA to recover following a continuous fatiguing contraction was cleverly demonstrated by Loscher and colleagues when they utilized an electrically elicited contraction to maintain an otherwise fatigued voluntary contraction (continuous contraction at 30% MVIC of the ankle plantarflexors) (Loscher, Cresswell et al. 1996). Following the initial fatiguing continuous voluntary contraction the electrical stimulation maintained the force output at 30% of MVIC for one minute after which the subjects maintained the contraction at the 30% of MVC level voluntarily for an average of 85±48 seconds. At the limit of endurance of the first voluntary contraction the superimposed evoked twitch was larger than during the prefatigue MVIC, indicating an impairment of VA. However, the size of the superimposed twitch after the second voluntary contraction was not different than the size of the superimposed twitch during the prefatigue MVIC. The period of electrically elicited contraction continued metabolic stress and contractile fatigue processes; however, it allowed recovery of the central mechanisms of muscle force production (Loscher, Cresswell et al. 1996).

In summary, muscle fatigue is defined as any exercise-induced reduction in the ability of a muscle to generate force or power; and failure of central and/or peripheral mechanisms lead to its development. The ITT is commonly utilized to examine the contribution of failure of central mechanisms to the overall development of fatigue, and if employed optimally represents a valid measurement tool. Use of the ITT in the study of

fatigue has demonstrated that different muscles demonstrate varying degrees of susceptibility to central fatigue and the development of central fatigue is dependent on the task performed. Identification of interventions to delay the onset of central fatigue or minimize the extent to which it develops was the focus of our second study (Chapter 3).

Training Effects on Voluntary Activation

When sensitive ITT is applied to unfatigued muscles, incomplete VA has been demonstrated in muscles of the upper (Dowling, Konert et al. 1994; Allen, McKenzie et al. 1998; Behm, Whittle et al. 2002; Williams and Bilodeau 2004) and lower extremities (Suter E 1996; Roos, Rice et al. 1999; Behm, Whittle et al. 2002) and the diaphragm (McKenzie, Bigland-Ritchie et al. 1992), a muscle of respiration. When fatiguing contractions are performed the level of VA diminishes (Bigland-Ritchie, Jones et al. 1978; McKenzie, Bigland-Ritchie et al. 1992; Gandevia, Allen et al. 1996; Kawakami, Amemiya et al. 2000; Williams, Sharma et al. 2002; Bilodeau 2006), demonstrating the contribution of central fatigue to the overall degree of neuromuscular fatigue. Furthermore, VA has been shown to be significantly decreased when tested in muscles that cross a painful joint, a swollen joint, and/or a joint that is injured (Snyder-Mackler, De Luca et al. 1994; Snyder-Mackler, Delitto et al. 1995; Harridge, Kryger et al. 1999; Urbach, Nebelung et al. 1999; Manal and Snyder-Mackler 2000; Lewek, Stevens et al. 2001; Stackhouse, Stevens et al. 2001; Urbach, Nebelung et al. 2001; Berth, Urbach et al. 2002; Machner, Pap et al. 2002; Machner, Pap et al. 2002; Urbach and Awiszus 2002; Mizner, Stevens et al. 2003; Becker, Berth et al. 2004; Chmielewski, Stackhouse et al. 2004; Lewek, Rudolph et al. 2004; Pap, Machner et al. 2004). These well-documented deficits in VA lead us to an obvious question: How do we best train an athlete or patient to maximize their level of VA to either enhance their athletic performance or optimize their rehabilitation from injury? Several studies have examined the effect of voluntary resistance training on the level of VA in healthy subjects and have demonstrated a

variable range of outcomes. Voluntary training of the quadriceps femoris has been found to elicit outcomes ranging from no change up to a significant 16.5% increase in the level of VA (Jones and Rutherford 1987; Carolan and Cafarelli 1992; Garfinkel and Cafarelli 1992; Hurley and Scott 1998; Harridge, Kryger et al. 1999; Knight and Kamen 2001). Ankle plantar flexor training has elicited up to a significant 4.2% increase in the level of VA (Scaglioni, Ferri et al. 2002; Shima, Ishida et al. 2002) and training of the elbow flexors has been unable to elicit significant adaptation in the level of VA post-training (Brown AB 1990; Herbert, Dean et al. 1998). Consideration must be given as to why the outcomes of these studies are so variable. The first potential confounding factor to consider is whether or not the ITT was implemented correctly and in its most sensitive form. In four of the ten studies examining the effect of training on the level of VA the authors reported that complete VA was present prior to training, therefore no room for improvement was present (Jones and Rutherford 1987; Brown AB 1990; Carolan and Cafarelli 1992; Garfinkel and Cafarelli 1992). The fact that the authors reported complete VA brings into question the sensitivity of their technique, and examination of the technique used in these studies reveals limitations. All of these studies utilized a single pulse of electrical stimulation, and therefore did not attempt to enhance the signal to noise ratio and minimize the effect of compliance in the testing system and/or muscle system by using multiple stimuli (train). Furthermore, these studies did not control for the potential limitations brought by subjects, as they did not include a familiarization session, provide verbal and visual feedback, and provide rejection criteria for contractions the subject felt were less than maximal or contractions in which the stimulation was applied inappropriately. The study by Carolan and Cafarelli (Carolan and Cafarelli 1992) was the only study of these four to include EMG monitoring of the antagonist hamstring group, therefore it is unknown in the other three if antagonist activity could have minimized the level of interpolated force. None of these studies reported the sensitivity of the force measurement system they utilized, and therefore it is

not known whether or not they possessed the ability to resolve small increments in force superimposed on the subject's MVICs.

Two other studies reported insignificant increases in VA after training: an insignificant increase in VA from 81% to 85% of the quadriceps by Harridge, and an insignificant increase from 96.2% to 96.9% of the biceps brachii by Herbert and colleagues (Herbert, Dean et al. 1998; Harridge, Kryger et al. 1999). The study by Herbert, Dean, and Gandevia (Herbert, Dean et al. 1998) brings to light an important consideration is deciding on a muscle to study the training induced adaptations in VA. Studies have demonstrated that some muscles are more readily brought to complete VA than others (Bellemare, Woods et al. 1983; McKenzie, Bigland-Ritchie et al. 1992), and therefore choosing to study the biceps brachii, a muscle which has been shown to possess a high level of VA may represent a poor choice (Williams, Sharma et al. 2002; Williams and Bilodeau 2004).

The four studies which demonstrated significant increases in VA following voluntary strength training implemented the ITT in the recommended manner to maximize technique sensitivity and were conducted on the quadriceps (Hurley and Scott 1998; Knight and Kamen 2001) and ankle plantar flexors (Scaglioni, Ferri et al. 2002; Shima, Ishida et al. 2002). These muscles were tested in lengthened positions, supramaximal stimulation was utilized, familiarization sessions were given, verbal and visual feedback was provided, and in one of the four studies sensitivity of the force measurement system was identified (Knight and Kamen 2001). The most frequent outcome measure utilized in all of the studies was the change in the peak value of VA. These studies support the premise that the level of VA will adapt to voluntary strength training and can be demonstrated when sensitive ITT is utilized. However, factors related to both training and testing could also limit adaptations of VA to voluntary strength training and must be considered when both interpreting and planning training studies.

Errors in testing and training procedures could account for some of the variability demonstrated in studies of the adaptation of VA to voluntary strength training. Most notably violation of the principle of testing and training specificity would significantly alter a study's outcome. Specificity of training refers to the relationship between the methods of training and the training outcomes. Specificity has been demonstrated for position, contraction type (isometric, isotonic, isokinetic), muscle length/joint angle, training intensity and volume, and contraction velocity (DeLorme 1945; Rasch 1957; Moffroid and Whipple 1970; Lesmes, Costill et al. 1978; Lindh 1979; Caiozzo, Perrine et al. 1981; Sargeant, Hoinville et al. 1981; Anderson and Kearney 1982; Rutherford, Greig et al. 1986; Narici, Roi et al. 1989; Stone 1994; Campos, Luecke et al. 2002; Fleck SJ 2004). Rasch and Morehouse demonstrated the concept of position specificity when they trained elbow flexors with subjects standing and conducted post-training testing in both standing and supine. Their results clearly demonstrated position specificity with subjects demonstrating significantly greater elbow flexor strength in the standing (familiar) as compared to the supine (novel) position (Rasch 1957). Specificity to the type of contraction used in training was demonstrated by Rutherford et al. (Rutherford, Greig et al. 1986) when they found a 200% increase in isotonic quadriceps strength and only a 15% increase in isometric quadriceps strength following a 12-week isotonic leg extensor strength training program utilizing near maximal contractions. When adaptations in isotonic and isokinetic strength have been compared, the concept of contraction type specificity has also been demonstrated. Sargeant and colleagues (Sargeant, Hoinville et al. 1981) trained the quadriceps femoris isotonically, and isokinetically assessed power output via modified cycle ergometry after the isotonic training. They found no change in isokinetic power output following isotonic training even though the quadriceps femoris was the primary agonist in both the training and testing tasks.

In the ten studies examining the effect of voluntary strength training on the level of VA the concept of specificity of position and contraction type have frequently been

violated. Hurley and Scott (Hurley and Scott 1998) and Knight and Kamen (Knight and Kamen 2001) utilized both isometric and isotonic muscle contractions in their training regimes, but always tested the subjects with isometric contractions. In these studies the effect of the mixed training contractions may not be as potentially deleterious secondary to the fact that the same contractions utilized in testing (isometric) were always included in the training. However, the studies by Brown and Sale (Brown AB 1990; Harridge, Kryger et al. 1999), Harridge et al.(Harridge, Kryger et al. 1999), Jones and Rutherford (Jones and Rutherford 1987), Scaglioni et al.(Scaglioni, Ferri et al. 2002), and Shima et al.(Shima, Ishida et al. 2002) utilized only dynamic or isotonic contractions in their training while always using isometric contractions in their testing. This complete absence of isometric contractions in the training regime could account for some of the lack of adaptation in the level of VA demonstrated post training in the study by Harridge et al.(Harridge, Kryger et al. 1999). Lindh (Lindh 1979) demonstrated that training induced increases in muscle strength are greatest at the muscle length/joint angle of training. She trained subjects' quadriceps femoris isometrically at either 15° or 60° of knee flexion and tested isometric strength of both groups at both angles. The groups demonstrated approximately a 30% increase in strength at the angle of training and only a 12% increase at the novel angle. As outlined above, the studies which incorporated dynamic or isotonic training contractions but utilized only isometric testing would have violated the concept of muscle length/joint angle specificity because these training contractions would have taken the involved muscles and joints through a wide range of lengths/angles as compared to the set muscle length/joint angle of testing.

Specificity of training volume and intensity refers to the fact that the adaptations in muscle force production and endurance that are caused by resistance training will depend on the specific training volume and intensity utilized in the training program (Fleck SJ 2004). DeLorme (DeLorme 1945) first proposed the strength-endurance continuum in 1945, and it has since come to be known as the repetition maximum

continuum (Fleck SJ 2004). The continuum demonstrates that the number of repetitions allowed by the load will result in very specific training adaptations, with high loads (high intensity) which allow few repetitions eliciting the greatest adaptations in muscle force production while low loads (low intensity) which allow a large number of repetitions to be performed eliciting the greatest adaptations in muscular endurance. A number of studies have validated the repetition maximum continuum theory (Anderson and Kearney 1982; Stone 1994; Campos, Luecke et al. 2002). For example, Anderson and Kearney (Anderson and Kearney 1982) utilized three different strength training regimes in forty-five college-aged men. The men were assigned to one of three training groups: high resistance/low repetitions, medium resistance/medium repetitions, and low resistance/high repetitions, and followed their training regime 2x/week for 9 weeks. As would be predicted by the continuum, the greatest gain in maximal strength, assessed with one repetition maximum (1RM) testing, was demonstrated by the high resistance/low repetition group (20.22% increase) followed by the medium resistance/medium repetition group (8.22% increase) and the low resistance/high repetition group (4.92% increase). Relative endurance was assessed as the maximum number of repetitions completed with 40% 1RM, and the low resistance/high repetition group demonstrated the greatest gain (28.45% increase) followed by the medium resistance/medium repetitions group (22.45% increase) with the high resistance/low repetition actually demonstrating a decrease of 6.99% in their level of relative endurance.

In the studies examining the effect of voluntary training on the level of VA (Jones and Rutherford 1987; Brown AB 1990; Harridge, Kryger et al. 1999; Scaglioni, Ferri et al. 2002; Shima, Ishida et al. 2002) the use of suboptimal training parameters (intensity and volume) to elicit central adaptations may be responsible for some of the variability in the outcomes. The ITT is utilized to expose motor units that either have not been recruited and/or are not firing at their maximal frequency, therefore it makes sense that the intensity and volume of training utilized must be sufficient to ensure complete

recruitment of the motor unit pool and maximal motor unit firing frequencies. Based on the size principle of Henneman (Henneman, Somjen et al. 1965) it is known that as the force level of a muscle contraction increases progressively larger motor units are recruited. In the small muscles of the hand complete recruitment of the motor unit pool is achieved at approximately 50% of the maximum force level with the remainder of the force coming from modulation of motor unit firing frequency (Kukulka and Clamann 1981). In larger muscle groups, such as the deltoid (De Luca, LeFever et al. 1982), biceps brachii (Kukulka and Clamann 1981), and tibialis anterior (Van Cutsem, Feiereisen et al. 1997), the upper limit of motor unit recruitment is approximately 85% of the maximal force. Behm (Behm 1995) has suggested the use of a training intensity of 85% of 1RM or greater in resistance training studies attempting to elicit central adaptations.

Velocity specificity of the training and testing contractions is another variable that could influence the effect of voluntary training on the level of VA. Velocity specificity has been studied (Moffroid and Whipple 1970; Lesmes, Costill et al. 1978; Caiozzo, Perrine et al. 1981; Narici, Roi et al. 1989; Behm and Sale 1993). However, accurately interpreting the effects of training velocity on the rate and peak of MVIC force and EMG development is difficult. Isokinetic training studies have demonstrated the greatest increases in muscle force development at the specific velocity used in training, however a carryover effect in force development from high velocity training to low velocity testing is present (Moffroid and Whipple 1970; Lesmes, Costill et al. 1978; Caiozzo, Perrine et al. 1981). Narici and colleagues demonstrated this carryover when they trained subjects isokinetically at 2.09 rad/s and revealed a significant increase of 20.8% and 42.4% in force and EMG, respectively, when subjects were tested with MVIC's (Narici, Roi et al. 1989). This carryover to test velocities below the training velocity has also been demonstrated in subjects who trained with ballistically performed isometric contractions who were tested at various isotonic velocities (Behm and Sale 1993). The potential for

an interaction effect between training load and training velocity also makes interpretation of velocity specificity difficult. Subjects who are resistance trained with greater than 80% of maximal loads have demonstrated a constant improvement of 25% in peak torque over all test velocities with the exception of the highest test velocity where a 10% improvement has been demonstrated (Thorstensson, Karlsson et al. 1976; Thorstensson 1977). Therefore, if a high training load is utilized it would be expected that force production at testing velocities higher than the training velocities would be improved. When training load is high and equivalent between two training groups, and one group trains at a high velocity and the other at a low velocity, both groups demonstrate a significant improvement in muscle strength but the improvement demonstrated by the high velocity training group is significantly greater than that of the low velocity training group by 11% (Munn J 2005). Similarly, Aagard and colleagues (Aagaard, Simonsen et al. 2002) and Hakkinen and Komi (Hakkinen and Komi 1986) examined the effect of high load isotonic training at velocities below that of the outcome test and demonstrated significant increases in peak MVC force (Hakkinen and Komi 1986; Aagaard, Simonsen et al. 2002), rate of force development (Aagaard, Simonsen et al. 2002), peak EMG (Hakkinen and Komi 1986; Aagaard, Simonsen et al. 2002), and rate of EMG rise (Aagaard, Simonsen et al. 2002). Therefore, it appears that there is a carryover effect of both high velocity training to lower velocity testing and high force training at low velocities to force output during higher velocity test contractions.

Ten studies utilizing the ITT to examine the effect of voluntary strength training on the level of VA have been conducted, demonstrating variable outcomes. Much of this variability can be explained by suboptimal implementation of the ITT and/or violation of the concepts of training and testing specificity. Four of these ten studies, demonstrated significant increases in VA after voluntary strength training, suggesting that voluntary strength training promotes adaptation in the central mechanisms of muscle force production (Hurley and Scott 1998; Knight and Kamen 2001; Scaglioni, Ferri et al. 2002;

Shima, Ishida et al. 2002). The concept of specificity of training and testing is violated to varying degrees in these four studies, and several limitations of the ITT are left uncontrolled. Therefore, with careful attention paid to training and testing program design and optimal implementation of the ITT it is highly likely that increases in the level of VA post voluntary training could be greater than those that have been demonstrated. To date, no study has investigated whether or not a voluntary resistance training program can enhance a subject's resistance to central fatigue. The utility of the ITT as a model for studying central mechanisms of VA is based on the underlying premise of a linear interpolated twitch to voluntary torque relationship.

The intent of our first study (Chapter 2) was to assess potential distracting factors that could contribute to non-linearity of the interpolated twitch to voluntary torque relationship. Based on the results of this first study combined with the results of follow-up pilot work (Appendix A), two training intervention studies (Chapter 3 and 4) were pursued. The pilot work was conducted to validate the quadriceps femoris interpolated twitch to voluntary torque relationship. From this work valuable information was obtained in helping refine testing procedures in addition to providing us confidence in our ability to safely proceed with the repetitive nature of multiple testing and exercise training aspects in studies two and three.

By design the two training studies included control groups in order to identify and control for potential confounding placebo effects. The intent of the first training study was to investigate the effect of high volume isometric resistance strength training on central fatigue. The second training study focused on the concept of contraction velocity specificity by examining the effects of ramp (slow contraction velocity) versus ballistic (fast contraction velocity) type isometric contraction training and testing on VA and force production.

Specific Aims and Hypothesis

The global intent of this research was to confirm the validity of the interpolated twitch to voluntary torque model and then to utilize this technique in developing definitive criterion measures enabling the study of selected training strategies on central fatigue and velocity specific VA and force production outcomes. The following three specific aims and hypotheses were designed to investigate the individual components necessary to reach the global objective of this research.

Specific Aim 1: To assess in healthy young adults the contribution of non-stimulated synergists to the non-linearity of the interpolated twitch-voluntary torque relationship for elbow flexion contractions. (Chapter 2).

Hypothesis 1a: Simultaneous stimulation of the biceps brachii and brachioradialis at rest and during a voluntary contraction will elicit significantly greater torque than that elicited by stimulation of the biceps brachii only.

Hypothesis 1b: Simultaneous stimulation of the biceps brachii and brachioradialis will improve the linearity of the interpolated twitch-voluntary torque relationship of the elbow flexors as compared to stimulation of the biceps brachii alone.

Specific Aim 2: To investigate in healthy young adults the effects of high volume voluntary isometric strength training of the quadriceps femoris on the level of MVIC VA and force production prior to, during, and after a fatiguing protocol. (Chapter 3).

Hypothesis 2a: Subjects who voluntarily isometrically strength train the quadriceps femoris will demonstrate post-minus pre-training increases in MVIC VA and force production in the pre-fatigue state as compared to a control group who will demonstrate no change.

Hypothesis 2b: Subjects who voluntarily isometrically strength train the quadriceps femoris will maintain higher levels of MVIC VA and force production during a fatigue task as compared to a control group who will show no change.

Hypothesis 2c: Subjects who voluntarily isometrically strength train the quadriceps femoris will demonstrate post-minus pre-training higher levels and more rapid recover of MVIC VA and force production as compared to a control group who will demonstrate no change.

Specific Aim 3: To examine in healthy young adults the effects of ramp (slow contraction velocity) and ballistic (fast contraction velocity) isometric contraction strength training on the level of VA and force production of the quadriceps femoris during MVIC ramp and MVIC ballistic testing.(Chapter 4).

Hypothesis 3a: In ramp and ballistic MVIC, and MVIC ballistic testing both ramp and ballistic training groups will demonstrate greater post- minus pre-training changes in VA and force

production as compared to a control group who will show no change.

Hypothesis 3b: The ballistic contraction trained group will demonstrate the greatest post-minus pre-training changes in VA and force production as compared to the ramp contraction trained group for MVIC ballistic and ramp testing and submaximal ballistic testing.

Hypothesis 3c: Test-training specificity will be indicated by greater post-minus pre-training changes in VA and force during MVIC ramp testing compared to ballistic testing for the ramp contraction training group; and conversely higher VA and force production training changes during MVIC ballistic testing compared to ramp testing for the ballistic contraction trained group.

Operational Definitions

Agonist Muscle Group: The primary muscle or muscles that are most directly related to the initiation and execution of the target movement.

Ballistic Muscle Contraction: Fast contraction velocity (maximal volitional rate of VA and force production per unit time ~300 ms) type of muscle contraction which displays a characteristic triphasic pattern of muscle activity.

Central Fatigue: A progressive reduction in voluntary activation of muscles during a fatiguing task.

Central Mechanisms Of Muscle Force Production: Anatomic structures and physiologic processes of the central nervous system lying proximal to the alpha-motoneuron in the ventral horn of the spinal cord that are involved in the voluntary production of muscle force.

Fatigue Test: A long duration, low intensity (25% MVIC force), intermittent contraction fatigue task was utilized. Contractions were held for sixteen seconds with four seconds of rest between contractions, thus three contraction/rest cycles per minute were completed. The fatigue test continued until subjects could no longer maintain the 25% MVIC force level for five seconds. During the last four seconds of each third contraction a 100% MVIC effort was performed with ITT applied resulting in one minute interval MVIC force and VA assessment for data analysis. This fatigue test protocol represents the same intermittent submaximal fatigue test used by Behm and St. Pierre to successfully elicit central fatigue.

Fatigue Test Force Volume: The sum of each individuals force x seconds values for all fatigue test contractions.

Fatigue Test Predicted Value At End Point: From the fatigue test data individual subject MVIC force and VA versus fatigue test time regression lines and equations including: r^2 and SEE values were generated. From these individual regression lines group mean regression lines were created for MVIC force and VA. Using these group mean regression lines along with the group mean fatigue test total endurance time the fatigue test predicted value at end point was determined for both MVIC force and VA.

Fatigue Test Predicted Value At One Minute: From the fatigue test data individual subject MVIC force and VA versus fatigue test time regression lines and equations including: r^2 and SEE values were generated. From these individual regression lines group mean regression lines were created for MVIC force and VA. Using these group mean regression lines the fatigue test predicted value at one minute of the fatigue task was calculated.

Fatigue Test Regression Line Slope: From the fatigue test data individual subject MVIC force and VA versus fatigue test time regression lines and equations including: r^2 and SEE values were generated. From these individual regression lines group mean regression lines were created for MVIC force and VA. The slope of these group mean regression lines for MVIC force and VA were utilized as a measure of the rate of fatigue.

Fatigue Test Total Endurance Time: The total time in minutes of the fatigue test.

Initial Fatigue Response: The decrement in MVIC force and VA that occurred in the first minute of the fatigue test was documented as the initial fatigue response. The initial fatigue response was calculated by subtracting the fatigue test predicted value at one minute from the pre-fatigue value.

Interpolated Twitch Technique (ITT): A laboratory procedure utilized to evaluate the level of voluntary activation achieved in voluntary isometric contractions. In this procedure a single pulse, doublet, or train of electrical stimulation is both superimposed on a voluntary isometric contraction and delivered to the muscle at rest. When the electrical stimulation is superimposed on the voluntary contraction if all motor units have not been recruited and/or if they are not firing maximally an interpolated force/torque will be created. From this technique, the level of voluntary activation is then calculated using the formula: VA (%) = [1-(interpolated evoked twitch/control evoked twitch)] x 100.

Maximum Voluntary Isometric Contraction (MVIC): A volitionally performed maximal contraction, in which the internal and external torques are balanced. During these contractions constant feedback (visual and verbal) regarding performance is provided.

Muscle Fatigue: Any exercise-induced reduction in the ability of a muscle to generate force or power.

Peripheral Fatigue: A progressive reduction in force production resulting from fatigue occurring in the muscle distal to the neuromuscular junction.

Peripheral Mechanisms Of Muscle Force Production: Anatomic structures and physiologic processes lying distal to the alpha-motoneuron in the ventral horn of the spinal cord that are involved in the voluntary production of muscle force.

Pre-Fatigue Measures: Prior to performing the fatigue test subjects' MVIC force and VA outputs were measured, and are termed pre-fatigue measures.

Post-Fatigue Measures: From the end of the fatigue task subjects MVIC force and VA outputs were measured at set time intervals and are termed recovery measures (RC). RC measures were taken one minute (RC1), two minutes (RC2), five minutes (RC5), ten minutes (RC10), and twenty minutes (RC20) following completion of the fatigue task.

Ramp Muscle Contraction: Slow contraction velocity (controlled volitional rate of force per unit time ~2 sec) type of muscle contraction.

Synergist Muscle Group: A secondary muscle or muscles that contributes to the initiation and execution and execution of the target movement.

Voluntary Activation (VA): The level of central drive achieved during a voluntary isometric contraction at any target force. Complete VA represents a state in which all motor units are recruited and firing at their optimal rates.

CHAPTER 2

INVESTIGATION OF THE CONTRIBUTION OF UNSTIMULATED SYNERGISTS TO THE INTERPOLATED TWITCH TO VOLUNTARY TORQUE RELATIONSHIP

Introduction

The interpolated twitch technique (ITT), which originates from the works of Denny-Brown (1928) and Merton (1954), is the most commonly used method to assess the capacity to activate maximally a muscle or muscle group under volition [referred to hereafter as the extent or level of voluntary activation (VA)]. The technique involves the application of a pulse (or doublet or train) of supramaximal electrical stimuli to a nerve or directly to the muscle while an individual is performing a maximum voluntary isometric contraction (MVIC) (Behm, St-Pierre et al. 1996; Kent-Braun 1997). If the muscle is fully activated by the voluntary command, no additional force (or torque) will be produced by the supramaximal electrical stimulation. However, if all motoneurons have not been recruited or if they are firing at a submaximal rate, additional torque should be elicited by the superimposed electrical stimulation. We will refer to this extra torque as the interpolated twitch, even if, in the present study, a train of stimuli rather than a single pulse is superimposed on the voluntary contractions. The ITT has been used to assess the level of VA in different muscle groups with varying results (Merton 1954; Bigland-Ritchie, Jones et al. 1978; Berlanger and McComas 1981; Bigland-Ritchie, Johansson et al. 1983; Gandevia and McKenzie 1985; Gandevia and McKenzie 1988; Lloyd, Gandevia et al. 1991; McKenzie and Gandevia 1991; Allen, McKenzie et al. 1993). For example, maximal VA of the ankle dorsiflexors (Berlanger and McComas 1981) and quadriceps (Bigland-Ritchie, Jones et al. 1978; Bigland-Ritchie, Furbush et al. 1986) has been reported even in untrained subjects. In contrast, incomplete activation has been reported

in some subjects for ankle plantar-flexors (Berlanger and McComas 1981). Studies on elbow flexor muscles (as in the present study) have reported a wide range in the level of VA (Lloyd, Gandevia et al. 1991; Allen, Gandevia et al. 1994; Dowling, Konert et al. 1994; Allen, Gandevia et al. 1995; Yue, Ranganathan et al. 1999; Bilodeau, Erb et al. 2001; Bilodeau, Henderson et al. 2001; Williams, Sharma et al. 2002).

Several authors have also studied the relationship between estimates of the level of VA (or simply of the amplitude of the interpolated twitch) and voluntary torque (% MVIC). This has been done by implementing the ITT while subjects generate a series of submaximal contractions at different torque levels. In general, when a muscle is relaxed the stimulus results in a maximal evoked response; as the level of voluntary contraction increases, the evoked response decreases. The response can eventually disappear altogether, if an individual is able to activate maximally the muscle (group) of interest. The shape of the interpolated twitch-voluntary torque relationship has significance because it has been argued that the true maximum voluntary torque that an individual can generate is predictable from a single submaximal interpolated twitch (estimate of the level of VA), provided that the relationship between the interpolated twitch and voluntary torque is linear (Behm, St-Pierre et al. 1996; Behm, Baker et al. 2001).

Certain authors report a linear relationship between the interpolated twitch (usually normalized to a control twitch elicited at rest) and voluntary torque for the quadriceps muscle group (Chapman, Edwards et al. 1985; Rice, Vollmer et al. 1992). However, a number of studies have shown a non-linear relationship in muscles such as the ankle plantar-flexors and dorsiflexors and biceps brachii (BB) (Berlanger and McComas 1981; Rutherford, Jones et al. 1986; Dowling, Konert et al. 1994). Behm et al. (Behm, St-Pierre et al. 1996) suggest that such nonlinearity is due to the contribution of suboptimally activated synergists muscles (Behm, St-Pierre et al. 1996). They observed a linear relationship for the quadriceps, the only muscle complex responsible for knee extension, but a nonlinearity when assessing the relationship for ankle plantar-flexors by

stimulating the tibial nerve. They explained the inability of a single interpolated twitch to predict accurately an individual's maximum voluntary contraction (non-linear interpolated twitch-voluntary torque relationship) by the potential contribution of other muscles that can generate ankle plantar-flexion torque, such as the peroneus longus and brevis innervated by the superficial peroneal branch of the common peroneal nerve.

A nonlinear interpolated twitch-voluntary torque relationship has also been reported for the elbow flexor muscles, perhaps because of the potential contribution of sub-optimally activated synergistic muscles (Allen, McKenzie et al. 1998). Typically, VA has been documented for the BB (and brachialis) muscle, leaving the contribution of synergists such as the brachioradialis (BR) a potential confounding factor in determining the shape of the interpolated twitch-voluntary torque relationship. Interestingly, Allen et al. (Allen, McKenzie et al. 1998) compared the VA of BB and BR during elbow-flexion MVCs and found that the median level of VA for the BB was 99.1%, whereas that of the BR was significantly lower at 91.5%. They concluded that the lower (and more variable) level of VA of the BR could account for some of the described nonlinearity. Recent work (Herbert and Gandevia 1999; Stevens, Stackhouse et al. 2003) suggests that the precise nature of the nonlinear relationship between interpolated twitch torque and voluntary torque can have significant implications for estimations of the level of VA. The nonlinear relationship suggests that small variations in the size of the interpolated twitch can actually signify large differences in the level of VA. The purpose of the present study (Williams and Bilodeau 2000) was to determine whether the interpolated twitch-voluntary torque relationship changes significantly (i.e., becomes more linear) when BB and BR are stimulated simultaneously compared to the stimulation of BB in isolation.

Methods

Subjects

Data were collected from 10 healthy volunteers (9 men, 1 woman) with a mean age of 29.2 ± 8.80 years, mean height of 1.77 ± 0.11 m, and mean weight of 77.38 ± 12.70 kg. Subjects had no history of upper-extremity orthopedic or neurologic disorders that could influence muscle torque production or motivation. All subjects gave informed consent prior to participating in the study, which was approved by the University of Iowa Institutional Review Board.

Materials

Testing was conducted once on the right upper extremity. Subjects were seated in an apparatus that held the shoulder abducted 90°and 45° anterior to the frontal plane, the elbow flexed at 90°, and the forearm in a neutral position between pronation and supination. The elbow was supported on a padded shelf with the lateral epicondyle aligned directly below the center of a multi-axial force/torque transducer (JR3 Inc, Woodland, CA). The resolution of the force/torque measurement system used, was 0.0024 V, which was less than 1% of the control twitches. The forearm was stabilized in a padded wrist cuff attached to a metal arm extending from the transducer. Elbow flexion efforts were performed by pulling against the wrist cuff. The output of the channel of interest from the transducer (i.e., elbow flexion) consisted of a torque reading in Nm. The shoulders and waist were stabilized with a shoulder harness and waist belt to minimize unwanted movements at these locations.

Electromyographic (EMG) signals were recorded from the BB, BR, and triceps brachii muscles. The skin was lightly abraded with alcohol-soaked gauze, and three Ag-AgCl bipolar surface electrodes (8-mm pick-up area, 20-mm interelectrode distance) were placed longitudinally over the belly of the three muscles in a direction parallel to the muscle fibers. Specifically, the triceps brachii electrode was placed over the long head at

the midbelly region, the BB electrode was placed over the short head on the distal portion of the muscle (distal third), and the BR electrode was placed over the bulk of the brachioradialis about 2 cm distal to the elbow joint. The common reference electrode was placed over the dorsum of the tested hand. EMG signals were pre-amplified at the electrode site (x30) and fed into a differential amplifier with adjustable gain settings (x100-100,000; frequency range between 15 and 4,000 Hz; CMRR 87 dB at 60 Hz; Therapeutics Unlimited, Iowa City, IA). EMG signals and the elbow flexion torque signal were sampled at 2,000 Hz and stored on a computer for later analysis.

Electrical stimulation of both BB and BR consisted of supramaximal trains of five stimuli (rectangular pulses, 50 μs-1 ms, 100 Hz) given during voluntary contractions, and also with the muscles at rest (Figure 2-1). Electrical stimulation was delivered to the BR using a constant-voltage stimulator (Model S8800/SIU8T stimulus isolation unit; Grass Instrument Co., Quincy, Massachusetts), and to the BB using a constant-current stimulator (Model DS7A, Digitimer, Welwyn Garden City, England). Both muscles were stimulated directly with two self-adhesive surface electrodes (50 mm x 50 mm for BB, and 30 mm x 30 mm for BR). The cathode was placed over the most prominent part of the muscle belly and the anode over the distal portion of the muscle. A supramaximal level of stimulation was sought for both muscles by increasing stimulation intensity until no further increase in elbow flexion torque was noted. The stimulation of the BB muscle most likely activated the brachialis muscle (also an elbow flexor), and of the BR likely activated the extensor carpi radialis muscle (also an elbow flexor) (An, Hui et al. 1981; Allen, McKenzie et al. 1998), although this could not be verified experimentally. Therefore, it is possible that the differences between stimulation of BB compared to stimulation of BB and BR simultaneously actually reflect the additional contribution of two muscles (BR plus extensor carpi radialis) to that of two others (BB and brachialis) (Lloyd, Gandevia et al. 1991; Allen, Gandevia et al. 1994; Allen, McKenzie et al. 1998).

Procedures

Once subjects were stabilized in the apparatus, they performed six submaximal warm-up contractions in elbow flexion. Subjects then performed a total of four elbow flexion maximal voluntary isometric contractions (MVICs), two with superimposed stimulation of the BB and two with superimposed simultaneous stimulation of BB and BR. Subjects ramped up to their maximum torque in about 2 s, held the maximal effort for approximately 3-4 s, and then relaxed. During the holding portion of the contraction, two supramaximal trains of stimuli were delivered to BB or to BB and BR simultaneously to assess the extent of VA. Upon relaxing, two trains of electrical stimuli were delivered to BB or to BB and BR simultaneously to elicit control torque responses. A 2-min rest was allowed between each MVIC. A final MVIC, in which the ITT was not used, was also performed at the end of each session to assess the extent of fatigue. The average of the peak torque obtained in each of the four MVCs was calculated and used to determine the following target torque levels: 25, 50, 60, 75, and 85% MVIC. Subjects had to perform two contractions at each torque level under each of the two stimulation conditions (BB alone, and BB plus BR), for a total of 20 contractions. Submaximal contractions were held for the same duration as the MVICs (3-4 s). Electrical stimulation during these submaximal contractions was the same as used during and after the MVICs (Figure 2-1). The order of presentation of the different target torque levels was counterbalanced (high torque-levels always alternated with low torque-levels), and the presentation of BB or BB and BR stimulation was always alternated within and across subjects.

Data Analysis

The following torque measures were obtained: peak torque for each MVIC trial, torque at the time of stimulation for each submaximal and MVIC trial (average torque for the two stimulation trains), and evoked torque produced by trains of electrical stimuli to

BB, and to BB and BR simultaneously (extra evoked torque during voluntary effort and evoked torque with the subject at rest). The amplitude (root mean square; RMS) of EMG signals for all three muscles was calculated for each trial. RMS was calculated over a 500-ms window centered between the two interpolated twitches for a given contraction. The average value from the two trials at each torque level for a given stimulation condition was calculated for each of the torque variables and EMG amplitude. This average value was utilized for statistical analyses.

The interpolated twitch-voluntary torque relationship was evaluated by first plotting the normalized extra torque produced by the stimulus trains (expressed as a percent of the torque obtained from the same stimulation at rest) against the normalized voluntary torque (% MVIC). Figure 2-2 shows such data from the two stimulation conditions of one subject. To characterize the shape of the relationship, both linear and second-order polynomial models were fit to the data. From those, the intercept, slope, and coefficient of determination (r^2) were obtained. For each MVIC, the activation index was calculated from the control twitch torque at rest and the extra torque elicited during the maximal effort using the formula: VA (%) = [1 – (interpolated evoked twitch/control evoked twitch)] x 100.

Two-way repeated measures analysis of variance models were used to assess the effect of the stimulation condition (BB alone versus simultaneous stimulation of BB and BR) and the target torque (25, 50, 60, 75, 85, 100% MVC) on torque variables (Table 2-1) and EMG amplitude, and the effects of stimulation condition and model type (linear versus polynomial) on r^2. Paired t-tests or the non-parametric equivalent were utilized where appropriate to depict significant differences between pairs of variables of interest. The level of significance was set at 0.05.

Results

Torque variables

Table 2-1 presents the torque variables obtained at each target level. No significant difference was found in the voluntary torque produced at each target level when comparing contractions where the two different stimulation protocols were used ($p>0.05$), which indicates that subjects were able to produce a similar torque level across the four trials at each target. The torque values listed for the MVIC trials are not 100% because the actual torque at the time of stimulation did not necessarily coincide with the peak torque for a given MVIC. The average MVIC torque for our sample was 111.7 ± 30.0 Nm.

With the simultaneous stimulation of BB and BR at rest, the elicited torque was about 73% greater than the torque recorded in response to BB stimulation ($p<0.05$, see also Figure 2-1). This indicates that we were successful in activating more synergists to elbow flexion with BB and BR stimulation than with BB stimulation alone. A main effect of target torque and the interaction between stimulation condition and target torque were also significant ($p<0.05$). This reflects the larger potentiation of the control torque elicited at rest following higher target torques (more pronounced for BB stimulation). In contrast to the results of the control torque elicited at rest, the extra torque produced by simultaneous BB and BR stimulation during voluntary efforts was not greater than that produced by stimulation of BB ($p>0.05$, Table 2-1, Figure 2-1). The decrease in the extra torque with increasing target torques was significant ($p<0.05$), and there was no significant interaction effect between target torque and stimulation condition ($p>0.05$). The MVIC torque produced at the end of the session was 109.1 Nm, which was 3% lower compared to values obtained at the beginning of the session. This small difference even though reaching statistical significance ($p<0.05$) was within the trial-to-trial within-

subject variability (~5%). Therefore, it was not deemed important and will not be discussed further.

Activation Index

A significant difference was found in the activation index calculated for the MVIC trials between the two stimulation protocols [the Wilcoxon signed rank test (nonparametric equivalent of paired t-test) was used because the activation index data were not normally distributed; $p<0.05$]. Simultaneous stimulation of BB and BR led to a higher activation index than stimulation of BB only, with a mean activation index of 95.0 and 91.7%, respectively (Figure 2-3).

Interpolated twitch-voluntary torque relationship

Scatter plots of the extra torque produced by the trains of electrical stimuli (interpolated twitch) compared with voluntary torque were generated for each subject (Figure 2-2). The r^2 values for these relationships (linear and polynomial models) are displayed in Table 2-2 for each subject. In both stimulation conditions (BB, and BB plus BR), a polynomial model always provided a better fit to the data (higher r^2 value) compared to a linear model, which was significant (main effect of stimulation condition, $p<0.05$) both for BB and for BB and BR simultaneous stimulation. When comparing the two stimulation conditions, r^2 improved with the simultaneous stimulation of BB and BR compared with BB only. The mean r^2 increased from 0.83 ± 0.08 with BB stimulation to 0.88 ± 0.08 with simultaneous stimulation of both BB and BR for the linear model and from 0.95 ± 0.06 to 0.97 ± 0.03 for the polynomial model. The interaction between stimulation condition and model type was significant ($p<0.05$), indicating a greater increase in r^2 for the linear fit when the simultaneous stimulation of BB and BR was compared to that of BB only. However, the general increase in r^2 for the linear fit when the simultaneous stimulation of BB and BR was relatively modest, as is reflected in the almost identical graphical representation of the data with both stimulation protocols

(Figure 2-4). The main effect of stimulation condition on the r^2 value did not reach statistical significance ($p=0.20$).

EMG Amplitude

No significant differences ($p>0.05$) were found in EMG RMS amplitude for the three muscles between contractions where the two different stimulation protocols were used. The mean EMG RMS values across all target torques and subjects were (in arbitrary units): BB, 0.60 ± 0.26 for BB stimulation and 0.62 ± 0.26 for combined (BB and BR) stimulation; BR, 0.24 ± 0.11 for BB stimulation and 0.24 ± 0.11 for combined stimulation; and triceps brachii, 0.05 ± 0.01 for BB stimulation and 0.05 ± 0.01 for combined stimulation. These data also indicate that subjects were consistent in their performance of the four trials for each target torque, and that antagonist coactivation did not vary between stimulation protocols.

Discussion

Our results suggest that suboptimal activation of the BR muscle contributes only minimally to the nonlinearity of the interpolated twitch-voluntary torque relationship observed for the elbow flexor muscles. The r^2 value did increase with the simultaneous stimulation of BB and BR compared with the stimulation of BB alone in most subjects, and this was more pronounced for the linear model. Thus, the unexplained variability in the data when a linear relationship was assumed was smaller with the simultaneous stimulation of BB and BR compared with that of BB. The magnitude of the difference in r^2 between the two stimulation protocols was relatively small (5%), and a second-order model provided a better fit to the data with the simultaneous stimulation of both agonistic muscles. However, recent studies (Herbert and Gandevia 1999; Stevens, Stackhouse et al. 2003) have suggested that small variation in estimates of VA may actually translate into significant differences in the actual level of VA. The nonlinear nature of the interpolated twitch-voluntary torque relationship implies that small changes in the

magnitude of the interpolated twitch are associated with larger changes in voluntary torque (Figure 2-4). Therefore, even relatively small variations in the precise relationship between interpolated twitch and voluntary torque, as found here between the two stimulation protocols, may actually be meaningful.

Because of the nonlinearity in the interpolated twitch-voluntary torque relationship, the r^2 value improved in all instances when a second-order compared to a linear model was fit to the data. This is consistent with the findings of others (Behm, St-Pierre et al. 1996; De Serres and Enoka 1998; Stackhouse, Dean et al. 2000; Behm, Baker et al. 2001; Stackhouse, Stevens et al. 2001) who concluded that second-order models should be used to describe the interpolated twitch-voluntary torque relationship. In fact, authors have recently used such models to estimate the extent of VA in various muscles (Behm, Whittle et al. 2002) as opposed to obtaining such an estimate through the more common performance of maximum efforts only, even though the estimation of VA from such maximal efforts can lead to reasonably adequate estimates (Behm, Baker et al. 2001).

Nonlinearity of the relationship

Because the second-order model provided a better fit to the data from both stimulation protocols, factors other than the contribution of the submaximally activated BR muscle appear to be more important in explaining the nonlinear relationship between the size of the interpolated twitch and voluntary torque for the elbow flexor muscle group. Such factors could include the contribution of other synergistic muscles not stimulated in our protocol, series compliance, and antidromic conduction. As mentioned earlier, stimulation of BB most likely activated the brachialis muscle, and of the BR likely activated the extensor carpi radialis muscle as well (Allen, McKenzie et al. 1998). A submaximal level of VA in these two muscles (and perhaps others, such as pronator teres) could contribute to the nonlinearity in the interpolated twitch-voluntary torque

relationship. An et al. (1981) estimated the potential moment contribution of each muscle at the elbow joint to elbow flexion-extension by multiplying the muscle's moment arm by its physiologic cross-sectional area. Based on these calculations, they estimated that in the position used in our study (90^{o} of flexion), the BB contributes 31.6%, extensor carpi radialis 29.2%, brachialis 27.4%, and BR 11.8% of the total moment. The electrically elicited torque with the muscle at rest was on average 29.4% MVC and 50.8% MVIC, respectively, for stimulation of BB alone and simultaneously with BR. Because we used supramaximal stimulation, we believe that the brachialis and extensor carpi radialis most likely were close to being fully activated by the stimulation. This is supported by the ~ 73% increase in torque with additional stimulation of the BR (and extensor carpi radialis) compared to that with electrodes only over the BB, as this increase corresponds to the predicted additional contribution of BR and extensor carpi radialis to that of BB and brachialis (An, Hui et al. 1981). Therefore, we do not believe that other suboptimally stimulated synergist muscles contributed significantly to the nonlinearity in the interpolated twitch-voluntary torque relationship.

Several authors have suggested that series compliance may contribute to the nonlinearity of this relationship (Loring and Hershenson 1992; Behm, St-Pierre et al. 1996; Allen, McKenzie et al. 1998). Allen et al. (1998) examined the effect of the series elastic component of muscle on system compliance during the measurement of voluntary drive at high torque levels by comparing the results obtained with single, paired, or a train of stimuli. A train of four stimuli elicited a larger response than either a doublet or single pulse. However, as voluntary torque increased, the amplitude of the response evoked by the different stimuli decreased. Above 85% MVC, the evoked responses were small and similar in amplitude regardless of the stimuli used to elicit them. Similarly, in the present study, even though the simultaneous stimulation of BB and BR elicited greater torque with the muscle at rest, the extra torque produced by either stimulation protocol was not different when superimposed on a voluntary contraction. This was

observed, not only for contractions performed at high voluntary torques, but for the whole range of submaximal contractions. Therefore, it appears that the relative independence of the extra torque on stimulation parameters (single, doublets, trains, or, in this study, BB vs. BB plus BR) compared to the differential effect observed at rest could influence the results of the ITT.

Factors such as antidromic conduction may have a predominant role in explaining the nonlinearity in the interpolated twitch-voluntary torque relationship. Herbert and Gandevia[21] modeled the human adductor pollicis motoneuron pool and investigated factors affecting the interpolated twitch. They concluded that the amplitude of the interpolated twitch is influenced by reflex and antidromic effects. Antidromic potentials slightly reduce the amplitude and duration of the interpolated twitch, which would affect the interpolated twitch-voluntary torque relationship.

Estimation of the level of voluntary activation

Our finding of a significantly higher activation index with the simultaneous stimulation of BB and BR compared to BB alone was somewhat surprising. Because the BR muscle reportedly has a lower activation level than the BB, it was expected that the simultaneous stimulation of both synergists would lead to the measurement of a lower level of VA (Allen, McKenzie et al. 1998). As stated above, the simultaneous stimulation of BB and BR elicited approximately 40-45% greater torque at rest than stimulation of BB alone. When calculating the activation index using the common formula: [(1-extra torque/control torque) x 100], greater torque at rest will lead to an increase in the denominator in the equation. In contrast, the difference in the extra torque elicited during a voluntary contraction between the two stimulation protocols did not reach significance. Therefore, the numerator in the equation would not be different between the two stimulation protocols. Consequently, our findings of a higher activation index for the simultaneous stimulation of BB and BR can be explained by the significant

increase in the torque at rest compared with stimulation of BB alone, paired with the relative independence of the extra torque on stimulation protocol. The implication of this finding is that potential differences in the magnitude of the extra torque elicited at rest (control torque) need to be controlled when comparing estimates of VA between different conditions or different groups of subjects. For example, several studies have looked at differences in the level of VA between young and old adults (De Serres and Enoka 1998; Yue, Ranganathan et al. 1999; Bilodeau, Erb et al. 2001; Bilodeau, Henderson et al. 2001). In order for such comparisons to be valid, the magnitude of the control twitch (as a percent of the MVIC torque) should be similar in the two groups.

Summary and Conclusions

In conclusion, it appears that suboptimal activation of the BR muscle contributes only minimally to the nonlinearity of the interpolated twitch-voluntary torque relationship observed for the elbow flexor muscles. However, a significant difference was observed in the level of VA when both BB and BR were stimulated simultaneously (higher level of VA) compared to the stimulation of BB alone (lower level of VA). This could have implications with regards to the comparison of VA levels across different conditions or subjects.

Table 2-1 Torque variables at each submaximal target level and during MVC trials (mean ± SD, n = 10)

Torque Level %	Voluntary Torque [BB] (% MVC)	At Rest Torque [BB] (% MVC)	Extra Torque [BB] (% Control)	Voluntary Torque [BB +BR] (% MVC)	At Rest Torque [BB + BR] (% MVC)	Extra Torque [BB +BR] (% Control)
25	23.78 ± 1.55	27.52 ± 9.56	68.49 ± 16.29	24.43 ± 1.27	50.60 ± 17.03	64.09 ± 8.83
50	46.52 ± 1.87	28.53 ± 10.04	30.46 ± 13.86	47.15 ± 2.33	50.74 ± 16.88	29.61 ± 11.41
60	56.27 ± 2.95	28.66 ± 10.01	19.32 ± 8.45	56.30 ± 3.33	50.48 ± 16.97	21.71 ± 9.89
75	69.91 ± 3.34	29.54 ± 10.42	9.98 ± 6.32	70.41 ± 2.31	50.82 ± 16.54	10.79 ± 5.83
85	79.39 ± 2.40	30.22 ± 11.16	4.58 ± 3.20	79.42 ± 2.32	50.53 ± 16.58	5.90 ± 4.25
MVC	91.11 ± 4.41	31.69 ± 11.16	4.92 ± 7.59	90.37 ± 5.10	51.77 ± 18.78	3.72 ± 4.57

At rest torque, torque (peak amplitude) with the trains of stimuli given at rest; BB, biceps brachii; BR, brachioradialis; extratorque, additional torque (above voluntary) with trains of stimuli; MVC, maximum voluntary contraction; voluntary torque, torque at the time of two trains of stimuli were superimposed on a voluntary contraction.

Table 2-2. Individual r^2 values for the interpolated twitch-voluntary torque relationship for both the linear and polynomial models.

	Stimulation			
Subject	Biceps Brachii		Biceps Brachii + Brachioradialis	
	Linear	Polynomial	Linear	Polynomial
1	0.8238	0.9502	0.8914	0.9868
2	0.9274	0.989	0.9544	0.9967
3	0.7407	0.961	0.7386	0.9628
4	0.8255	0.9888	0.8458	0.9608
5	0.765	0.9446	0.7763	0.9504
6	0.9435	0.9724	0.9711	0.9925
7	0.7071	0.7733	0.9613	0.9893
8	0.9034	0.9876	0.8976	0.987
9	0.8044	0.9633	0.8833	0.9802
10	0.9071	0.9681	0.8688	0.9115
Mean ± SD	0.835 ± 0.083	0.950 ± 0.064	0.879 ± 0.077	0.972 ± 0.026

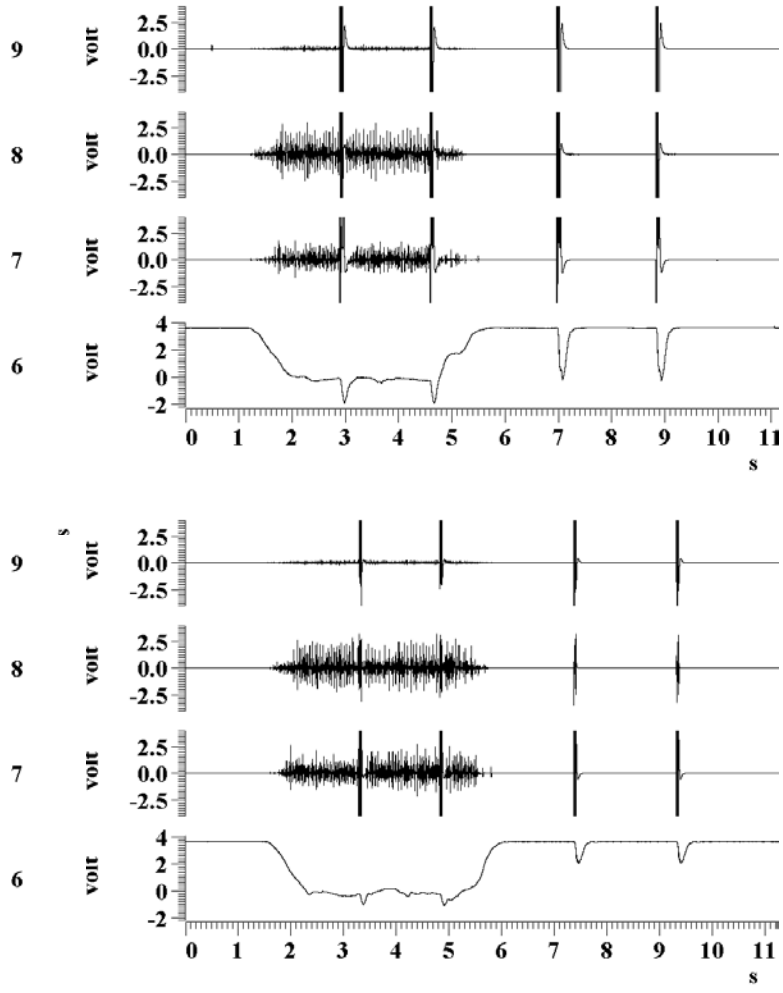


Figure 2-1.Examples of individual trials at a contraction level of 50% of MVC for subject 6.

Note: The interpolated twitch technique with stimulation of the biceps brachii only is shown on the bottom panel, and that with the simultaneous stimulation of the biceps brachii and brachioradialis is shown on the top panel. For each panel, electromyographic signals of the three recorded muscles and elbow flexion torque (labeled "mz"), are shown.

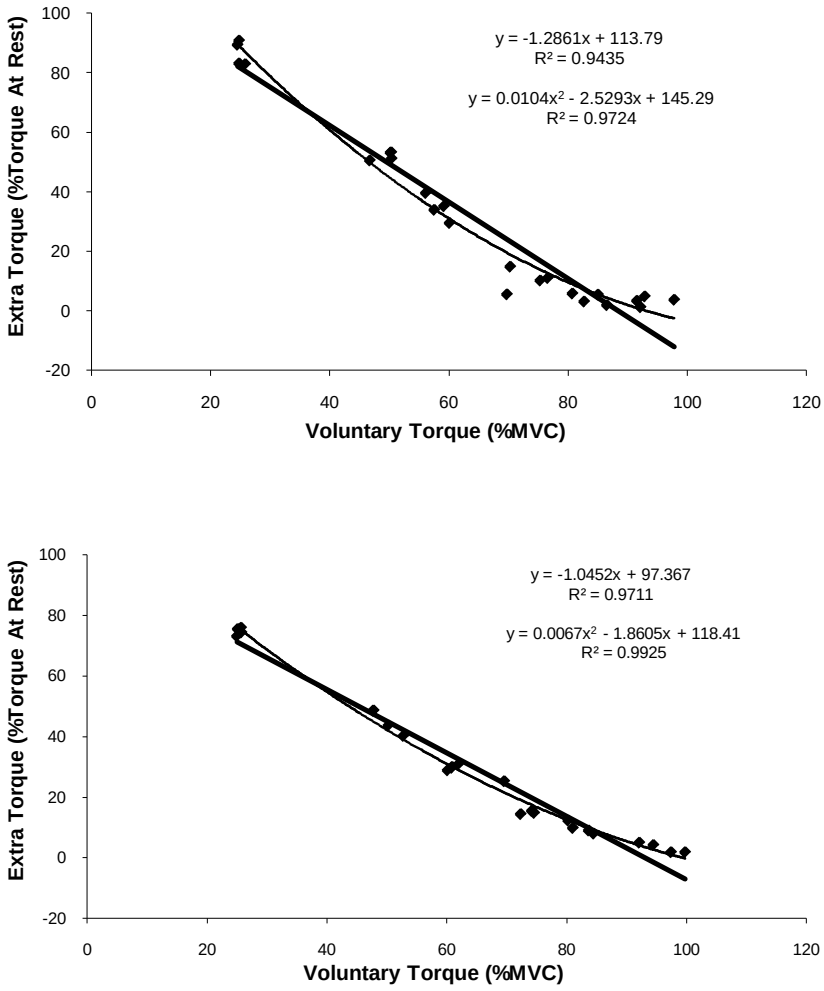
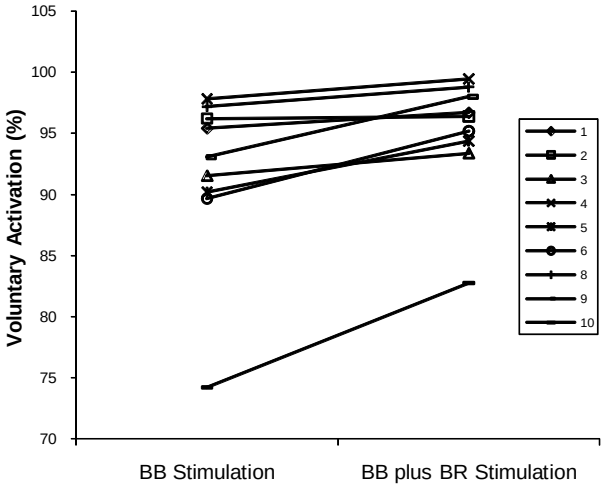


Figure 2-2 Interpolated twitch-voluntary torque relationship for each stimulation protocol (stimulation of biceps alone in the top panel, and of both biceps and brachioradialis in the bottom panel) of subject 6.

Note: Linear (solid line) and polynomial (dotted line) models were fit to the data, and their respective equations are displayed.

Figure 2-3 Level of voluntary activation obtained for MVC trials with stimulation of



biceps brachii, and simultaneous stimulation of biceps brachii and brachioradialis.

Note: Individual data from nine subjects are depicted. Data from subject 7 were not used for the MVC trials because of unreliable elicited torque measurements. All statistical analyses were performed with and without the data from this subject with the same outcomes.

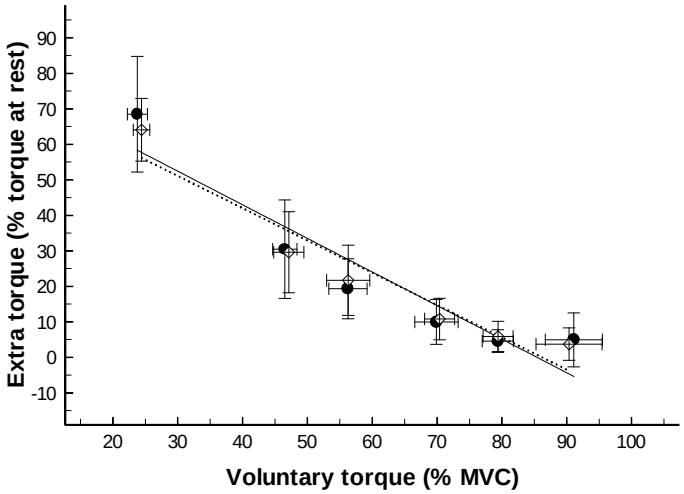


Figure 2-4 Composite (n=10) interpolated twitch-voluntary torque relationships obtained with the two stimulation conditions.

Note: Filled circles represent data for biceps stimulation, and open diamonds represent data for simultaneous stimulation of biceps brachii and brachioradialis.

CHAPTER 3

INVESTIGATION OF THE EFFECT OF HIGH VOLUME ISOMETRIC STRENGTH TRAINING OF THE QUADRICEPS FEMORIS ON LEVELS OF VOLUNTARY ACTIVATION AND MAXIMUM FORCE PRODUCTION PRIOR TO, DURING, AND AFTER A LONG DURATION FATIGUE TEST PROTOCOL.

Introduction

The ability of a subject to maximally voluntarily activate a muscle is commonly assessed using the interpolated twitch technique (ITT) or one of its variations in which a doublet or train of stimuli are superimposed on the voluntary contraction in lieu of a single pulse. The ITT examines the contribution of central mechanisms of muscle force production to the overall development of muscle force, and has been applied extensively to examine the contribution of central mechanisms of muscle force production to the development of muscle fatigue (Merton 1954; Bigland-Ritchie, Furbush et al. 1986; Newham, McCarthy et al. 1991; McKenzie, Bigland-Ritchie et al. 1992; Gandevia, Allen et al. 1996; Loscher, Cresswell et al. 1996; Behm and St-Pierre 1997; Kent-Braun 1999; Kawakami, Amemiya et al. 2000; Bilodeau, Henderson et al. 2001; Williams, Sharma et al. 2002; Schillings, Hoefsloot et al. 2003; Bilodeau 2006). It has been demonstrated in several muscles that the level of voluntary activation (VA) decreases with prolonged activity, and this decrease in VA has been defined as central fatigue (Bigland-Ritchie, Furbush et al. 1986; Gandevia, Allen et al. 1996; Behm and St-Pierre 1997; Kent-Braun 1999; Bilodeau, Henderson et al. 2001; Gandevia 2001; Schillings, Hoefsloot et al. 2003; Nordlund, Thorstensson et al. 2004). The mean non-fatigued level of VA of the quadriceps femoris, the muscle of interest in this study, has been reported to range from 90% to 98% in young healthy adults, however, the level of VA can be quite variable

across subjects (85%-100%) (Behm and St-Pierre 1997; Hurley, Rees et al. 1998; Roos, Rice et al. 1999; Stackhouse, Dean et al. 2000; Becker and Awiszus 2001; Stackhouse, Stevens et al. 2001).

Following prolonged muscle activity it has been demonstrated in the quadriceps (Bigland-Ritchie, Jones et al. 1978; Behm and St-Pierre 1997) and other muscles (Gandevia, Allen et al. 1996; Kent-Braun 1999; Bilodeau, Erb et al. 2001; Bilodeau, Henderson et al. 2001; Bilodeau 2006) that not all subjects develop central fatigue and that the extent to which central fatigue develops may be dependent on the task performed (McKenzie, Bigland-Ritchie et al. 1992; Williams, Sharma et al. 2002; Bilodeau 2006). Bigland-Ritchie et al.utilized an uninterrupted quadriceps femoris maximum voluntary isometric contraction (MVIC) held for 60 seconds as their fatigue task and they reported that the force dropped to about 30% of the initial level and that central fatigue developed in five of their nine subjects (Bigland-Ritchie, Jones et al. 1978). In those five subjects, central fatigue accounted for approximately 10 to 30% of the force loss. Behm and St-Pierre utilized two intermittent fatigue tasks to examine central fatigue of the quadriceps femoris (Behm and St-Pierre 1997). The contraction intensity largely guided the duration of the fatigue task, with the short duration fatigue task employing a contraction intensity of 50% MVIC while the long duration fatigue task employed a contraction intensity of 25% MVIC. They found a greater drop in VA of 12% following the long duration fatigue task as compared to a 6% drop in the short duration fatigue task. Despite the fact that failure of central mechanisms of muscle force production has been demonstrated numerous times following the completion of a fatigue task, only a few studies have documented the time course development of central fatigue as the fatigue task proceeds (Gandevia, Allen et al. 1996; Bilodeau, Erb et al. 2001; Bilodeau 2006). To date, no study has documented the time course development of central fatigue in muscles of the lower extremity, where the failure of central mechanisms of muscle force production could have significant implications in many functional tasks.

When comparing the functional relevance of continuous and intermittent fatigue tasks, the intermittent fatigue task more realistically represents the functional demands of everyday muscle use. Numerous examples of maximal contractions of lower extremity muscles interposed with ongoing submaximal contractions exist in daily life. In occupations dealing with manual materials handling, it is common for a worker to produce a maximal effort as they lift a heavy object and then produce a series of submaximal contractions as they carry the object, only to once again exert a maximal muscle contraction as they place the object. To produce repeated maximal contractions a high degree of VA is needed and must be maintained as the task proceeds throughout the workday. By monitoring the time course development of central fatigue in an intermittent submaximal fatigue protocol we will begin to develop an appreciation of the rate at which central fatigue develops. And by monitoring the level of VA at set time periods after the fatigue task we will also be able to examine the nature of recovery from central fatigue.

Even though central fatigue has been well documented in a number of muscles during several different fatigue protocols, studies examining the effect of intervention strategies to delay or prevent the occurrence of central fatigue are non-existent. Ten studies examining the effect of voluntary strength training on the level of VA in the non-fatigued state have been conducted revealing variable outcomes (Jones and Rutherford 1987; Brown AB 1990; Carolan and Cafarelli 1992; Garfinkel and Cafarelli 1992; Herbert, Dean et al. 1998; Hurley and Scott 1998; Harridge, Kryger et al. 1999; Knight and Kamen 2001; Scaglioni, Ferri et al. 2002; Shima, Ishida et al. 2002). Elbow flexor studies have either demonstrated very high VA prior to training (Brown AB 1990) or an insignificant increase of 3.7% with training (Herbert, Dean et al. 1998). In ankle plantar flexors significant increases in VA post-training ranging from 3% (Scaglioni, Ferri et al. 2002) to 4.2% (Shima, Ishida et al. 2002) have been demonstrated. In the quadriceps significant increases in VA ranging from 2% to 16.5% have been demonstrated in

younger and older healthy subjects and in older subjects suffering with knee osteoarthritis (Hurley and Scott 1998; Knight and Kamen 2001). Some of the variability in the outcomes of these studies could be explained by the use of suboptimal training parameters. Complete VA represents a state in which all motor units are recruited and firing at their optimal rate. This state of motor unit recruitment and firing rate is only achieved when a maximal contraction is performed. Only two of the training studies utilized maximal training loads, and both demonstrated a significant increase in the level of VA (Hurley and Scott 1998; Knight and Kamen 2001).

Since resistance training with maximum loads has been shown to increase the level of VA in the non-fatigued state, it seems logical that some variation of this approach may similarly be effective at slowing the rate and/or minimizing the extent to which central fatigue develops. Resistance training may also alter the rate and extent of recovery from central fatigue. Training which could alter either/or the development of or recovery from central fatigue could have significant implications in the realms of rehabilitation and athletic performance enhancement. However, to the author's best knowledge, no study has examined the effect of voluntary resistance training on the development of and/or recovery from central fatigue. Therefore, it is unknown if voluntary resistance training can meaningfully alter the development and recovery from central fatigue.

Results from our sister study (Chapter 4) showed that isometric strength training involving five second duration MVIC efforts was effective in significantly increasing maximum levels of VA and force production. In that study MVIC exercise repetitions were progressively increased from three sets of six repetitions per training session to three sets of ten repetitions per training session, completing a total training volume of 486 contractions in the six week training program. To enhance the endurance training component of our fatigue study MVIC exercise repetitions were held constant at three

sets of ten repetitions per training session and the training program was extended to eight weeks, resulting in a total volume of 720 completed contractions.

The purpose of this study was to investigate in healthy young adults the time course development of central fatigue and the effect of high volume voluntary isometric resistance training of the quadriceps femoris on the level of MVIC force and VA development prior to, during, and after a standardized fatigue test protocol.

Methods

Research Design: A randomized, controlled, repeated measures design was used to make pre- to post-training and between group (control and training) comparisons in MVIC force and VA measures prior to, during, and after a submaximal intermittent fatigue test. Although a randomized control design was used, because of the small number of subjects involved in the study, potential bias in the subject group assignment was a concern. Subsequently, between group analysis was done on the subject demographics as well as on pre-training outcome variables. Also, in order to minimize any potential pre-training group differences, post-minus pre-training change scores were utilized for the statistical analysis of all study outcome variables. A control group was utilized to analyze both placebo and training efficacy effects. High volume, high resistance exercise was utilized to optimize training intervention effects. Overall success of the training program was evaluated by analyzing the post- minus pre-training changes in pre-fatigue test MVIC VA and force. A long-duration, low-intensity intermittent muscle contraction fatigue test protocol was used in order to simulate functional repetitive fatigue type physical activity. In order to characterize the fatigue process MVIC VA and force measurements were recorded at one-minute intervals over the duration of the fatigue test. Subject response to fatigue was evaluated by analyzing post-minus pre-training changes in MVIC VA and force initial value at one minute of the fatigue test, the initial fatigue response (pre-training value minus fatigue value at minute

one), slope of the fatigue test response line (rate of fatigue), end point of the fatigue test response line, total time of fatigue test (seconds), and total force volume (amount of work performed during the fatigue test). A long-duration, multi-time interval post-fatigue test recovery protocol was used in order to ensure adequate measurement sampling to characterize the fatigue recovery process. In order to evaluate the recovery process MVIC VA and force at each recovery time interval were analyzed for post- minus pre-training changes (changes in level of recovery) as well as post-minus pre training changes between adjacent recovery time intervals (change in rate of recovery). All subjects were instructed to refrain from starting any new physical activity ventures for the duration of the study. Training group subjects were monitored throughout the eight-week training program to ensure compliance with exercise training.

Subjects: Originally nineteen healthy, young subjects were randomly assigned to either the control (9) or training (10) group. Inclusion criteria included: no history of neuromuscular or cardiovascular disease, no lower extremity or torso orthopedic disorder that could influence muscle torque production or motivation, ability to achieve at least 75% VA of the quadriceps femoris, and no participation in athletics (intramural, club, or varsity) or a scheduled exercise regime. Based on initial screening of MVIC VA readings one control subject was eliminated secondary to being unable to achieve ≥75% VA. Two additional control group subjects were eliminated secondary to non-compliance with the post-training fatigue test protocol. Two training group subjects developed patellofemoral pain and were unable to complete the study. The final control group included six subjects and the final training group included eight subjects. All testing and training was conducted on the dominant leg as determined by the leg that subjects would choose to kick a ball with. Subjects' activity level was determined using the Habitual Physical Activity Scale (Baecke, Burema et al. 1982) (Appendix B; subject characteristics are described in Table 3.1). The study was approved by the University of Iowa Institutional Review Board prior to collecting data. All subjects gave informed

consent prior to participating in the study. All subjects participated in one familiarization and two test sessions, with the training group also participating in twenty-four training sessions (8 weeks).

Experimental Set-Up: Subjects were seated in a custom designed chair with their knees and hips flexed to 45° and 85°, respectively, and back supported which was found in our pilot work (Appendix) to be the optimal test position. Stabilization straps were placed around the torso, pelvis, and thigh. The subject's leg was anchored perpendicular to the force transducer at a point 2.5 cm proximal to the medial malleoli. The knee flexion angle of 45° was set such that it represented a pre-tensioned measurement, thus helping to reduce measurement system compliance. Apparatus set-up was recorded to ensure accurate reproduction at test sessions.

Force Measurement: Maximal isometric quadricep femoris muscle contractions into knee extension and electrically elicited quadriceps femoris contractions were measured using an Interface Model 1210AF-300-B load cell. Resolution of the force measurement system is 0.75 N, which is less than 1% of the control twitch force. Force was sampled at 1000 Hz and the signal was stored on a computer for analysis. An oscilloscope (Tektronix TDS 460A) provided continuous visual feedback of the force signal. Force during MVIC's and force elicited by electrical stimulation at rest was quantified in Newtons by measuring the maximum force occurring at any point during the voluntary and elicited contractions. Data were analyzed using Spike 2 version 3.17 software (Cambridge Electronic Design, Cambridge, England).

ITT Measurement: The ITT test protocol was the same as that in our earlier published study: interpolated twitch voluntary torque relationship study (Chapter 2). Supramaximal percutaneous electrical stimulation was delivered to the quadriceps femoris using a Digitimer Model DS7A constant current stimulator. Supramaximal stimulation was demonstrated by the lack of additional increases in evoked force at rest with increasing stimulation intensity. Two stimulating electrodes (38x90 mm) were

placed with the cathode over the proximal quadriceps mass and the anode over the distal quadriceps. Trains of electrical stimulation (5 pulses, 0.05 ms duration, at 100 Hz) were utilized. Once maximal force was achieved during the MVIC test, electrical stimulation was superimposed at one second intervals on the brief three- to five-second maximum muscle contractions (Figure 3-1). In the pre-fatigue and recovery test contractions two trains of electrical stimulation were used, and during the fatigue protocol one train of electrical stimulation was used (Figure 3-2). Immediately after each of the brief MVICs one train of stimulation was delivered at rest. VA was calculated using the following formula: VA (%) = [1-(interpolated evoked twitch/control evoked twitch)] x 100. The level of VA was calculated for each of the pre-fatigue and recovery MVICs and once during each minute of the fatigue task.

Experimental Procedures:

Subject Warm-Up: Prior to familiarization, test, and training sessions subjects performed a general warm-up to ensure preparedness for MVIC testing/training. Subjects performed one repetition of static stretches for the quadriceps femoris and iliopsoas/rectus femoris which they held for 30 seconds. Subjects were then seated in the test/training apparatus, stimulating electrodes were placed on the quadriceps as outlined above, and subjects then performed five progressively graded isometric contractions of the quadriceps femoris (20, 40, 60, 80, and 100% MVIC) at the test angle of 45° knee flexion. The force level achieved during the 100% MVIC warm-up contraction was recorded and used in establishing target force levels for subsequent contractions.

Familiarization Session: All subjects participated in one familiarization session to get accustomed to the electrical stimulation and practice performing MVICs. The experimental protocol for MVIC testing pre fatigue was described in detail for the familiarization session and unique aspects of the testing and training sessions are highlighted in following sections. Upon completing the warm-up process as described

above, three minutes of rest were given prior to setting the stimulator intensity. Supramaximal stimulator intensity was set by delivering a train of stimulation to the relaxed quadriceps femoris and progressively increasing the intensity of stimulation (25 V increments) until one of two outcomes was achieved, either 1) the subject refused to increase stimulator intensity due to their inability to tolerate higher doses, or 2) the incremental increase in stimulator intensity did not elicit a greater control force than the previous intensity. The supramaximal stimulation intensity and the subsequent control force it elicited were recorded. Three minutes of rest followed the setting of stimulator intensity. Subjects then performed three quadriceps MVICs with three minutes rest between each contraction. Loud verbal encouragement and real-time visual feedback were provided as the subjects performed their MVICs. A target force level was set for each contraction, which was determined for the initial contraction as the force level achieved in the 100% MVIC warm-up contraction plus 10%. For subsequent contractions, the target force level was increased any time the subject achieved or exceeded their previous target level. In these cases the target was set as the new 100% MVIC maximum plus 10%. If a subject did not reach their force target, the same target was used in subsequent contractions. Subjects were instructed to attempt to exceed their target force in all contractions. For each of the quadriceps MVIC contractions, subjects ramped up to their maximum force level in about one second, held the maximal effort for three to four seconds, and then relaxed. Once the subject reached MVIC (visually determined) during the holding portion of the contraction, two supramaximal trains of stimuli were delivered to the quadriceps femoris one second apart to evaluate the extent of VA. Upon relaxing, one train of supramaximal stimulation was delivered to the quadriceps femoris at rest to elicit control responses. This concluded the familiarization session.

Testing Sessions: All subjects participated in initial and final test sessions, which were separated by eight weeks. Subjects completed the stretch portion of their warm-up,

were seated in the test apparatus, and stimulating electrodes were positioned, with positioning reproduced utilizing measures from their familiarization session. Subjects then performed five progressively graded isometric contractions of the quadriceps femoris (20, 40, 60, 80, and 100% MVIC) at the test angle of 45° knee flexion to complete their warm-up. The force level achieved during the 100% MVIC warm-up contraction was recorded and used to set the target force level for the first pre-fatigue MVIC. Target MVIC force levels and stimulator intensity were set as outlined in the familiarization session. Subjects then performed three pre-fatigue quadriceps femoris MVIC contractions with superimposed stimulation exactly as they had in the familiarization session. Variables of interest in the pre-fatigue data included MVIC force and VA. The maximum force level achieved in the three MVIC quadriceps contractions was used to set the target force level for the fatigue test, which consisted of low intensity (25% MVIC force) intermittent contractions with a work/rest ratio of 16/4 seconds resulting in three contraction/rest cycles per minute. The fatigue test continued until subjects could no longer maintain the 25% MVIC force level for five seconds. During the last four seconds of each third contraction a 100% MVIC effort was performed with ITT applied resulting in one minute interval MVIC force and VA recordings for data analysis (Figure 3-2). The above fatigue test protocol represents the same intermittent submaximal fatigue test used by Behm and St. Pierre to successfully elicit central fatigue (Behm and St-Pierre 1997). From the fatigue test data individual subject MVIC force (Figure 3-3) and VA (Figure 3-4) versus fatigue test time regression lines and equations including: r^2 and SEE values were generated.

Once the subject fatigued to the prescribed end point level of the fatigue test protocol, post-fatigue MVIC trials with ITT stimulation were performed with MVIC VA and force measurements at 1, 2, 5, 10, and 20 minutes of recovery. Recovery outcome variables of interest that were analyzed included recovery MVIC force and VA at: one minute of recovery (RC1), two minutes of recovery (RC2), five minutes of recovery

(RC5), 10 minutes of recovery (RC10), and 20 minutes of recovery (RC20). Fatigue test predicted end point MVIC force and VA values were included as an initial reference point of zero recovery (RC0).

Training: Isometric quadriceps strength training commenced no less than two and no more than four days after the initial test was performed. Training was conducted 3x/week for 8 weeks (24 training sessions). Training parameters consisted of three sets of ten repetitions of MVICs held for five seconds with ten seconds rest between contractions and three minutes rest between sets. Each training session proceeded as follows: 1) subjects completed the warm-up and were positioned in the testing/training apparatus, 2) the target MVIC force level was set for their first training set and was increased for subsequent training sets if the target force level was achieved in the prior set (in this manner the subject's training target was adjusted on a set by set basis throughout their course of training), and 3) subjects then completed their training contractions utilizing the parameters outlined above. Subjects were instructed to attempt to exceed their target force in all training contractions. Upon completing all training sessions, post-training testing was conducted between two and four days after the last training session. Training compliance was 100% in the training group (completed training sessions/total possible training sessions).

Data Analysis:

Variables Of Interest: The dependent variables of interest include: pre-fatigue data – MVIC VA and force levels; fatigue data – MVIC VA and force group mean regression line slope; predicted MVIC VA and force at minute one; initial fatigue (pre-fatigue minus predicted value at minute one) VA and force response; predicted end point VA and force, total endurance force volume (sum of individuals force x seconds values for all fatigue test contractions and endurance time (total seconds of fatigue test); and endurance time (seconds); recovery data – MVIC VA and force levels at designated

recovery times. The variables were quantified pre, during, and post fatigue and were compared as post- minus pre-training change scores.

Statistical Analysis: Descriptive statistics (group means and standard deviations for age, height, weight, BMI, and activity level) were calculated and non-paired t-tests were utilized to test for between-group differences. The statistical analysis of the pre-fatigue, fatigue, and recovery data was constructed to address four specific questions: 1) pre-training analysis to assess any potential between group-differences associated with subject assignment; 2) post- minus pre-training differences in the control group to test for a placebo effect; 3) post- minus pre-training differences in the training group to test for a general training effect; and 4) comparison of post- minus pre-training differences between the control and training group to assess for training efficacy. Non-paired t-tests were used to analyze the pre-training between groups differences for the pre-fatigue and fatigue data, while analysis for pre-training differences in the recovery data was accomplished using a two-way ANOVA with two levels of group (control and training) and six levels of recovery (RC0, RC1, RC2, RC5, RC10, RC20). Evaluation of the placebo (control group) and general training effects (training group) for the pre-fatigue, fatigue, and recovery data was completed using paired t-tests of the post- minus pre-training change scores. Analysis for training efficacy (post- minus pre-training control group change score vs. training group post- minus pre-training change score) for the pre-fatigue and fatigue data was accomplished using a one-way ANOVA with two levels of group (control and training). Training efficacy (post- minus pre-training control group change score vs. training group post- minus pre-training change score) for the recovery data was evaluated using a two-way ANOVA with two levels of group (control and training) and 6 levels of recovery time (RC0, RC1, RC2, RC5, RC10, RC20). The rationale for using post- minus pre-training change scores was to minimize the potential confounding effect of any pre-training group bias due to chance variation in initial subject group assignment. In addition the pre-training data were utilized as covariables in

the MVIC force efficacy ANOVA procedures. Initial attempts at using pre-training data as a covariable in the ANOVA analysis of VA resulted in non-significant f-tests for all VA analyses. Subsequently, pre-training covariable data were not used in the ANOVA for VA. A possible explanation for these results may be related to the empirical finding of a high negative correlation between pre-training VA and post- minus pre-training change scores for VA ($r \geq -0.91$). In this context, when pre-training VA was used as a covariable the ANOVA model negated all positive post- minus pre-training effects. Student's t-tests were used for follow-up pairwise comparisons with Bonferroni alpha adjustments when appropriate. All statistical analysis was conducted using SAS 9.2 TS Level 2M3 (SAS Institute, Inc. Cary, North Carolina, USA). An α level = 0.05 was adopted for statistical significance.

Results

Subject Characteristics**:** Group descriptive statistics are included in Table 3-1. The analysis of subject demographics revealed no significant between group differences for age, height, weight, BMI, and activity level. Pre-Fatigue Data Analysis: Group means and standard errors for the pre and post-training pre-fatigue MVIC force and VA data are graphically presented in Figure 3-5 and 3-6, respectively. Numeric values of the pre-training force and VA data are presented in Tables 3-2 and 3-3, respectively. Non-paired t-tests revealed non-significant pre-training between group differences for both MVIC force and VA. Paired t-tests of the MVIC force and VA post- minus pre-training change scores revealed non-significant control group placebo effects. Paired t-tests of the post-minus pre-training change scores for the training group revealed significant MVIC force and VA general training effects. One-way ANOVA of post- minus pre-training control vs. training group change scores demonstrated significant training efficacy results for both MVIC force and VA measurements. Fatigue Data Analysis: MVIC force and VA fatigue test group mean fatigue response (regression) lines are graphically presented in

Figures 3-7 and 3-8, respectively. Total endurance force volume results are graphically presented in Figure 3-9. Numeric values of the fatigue MVIC force and VA data are presented in Tables 3-2 and 3-3, respectively. Analysis of pre-training between group-differences revealed non-significant non-paired t-tests for all fatigue test outcome variables. Control group placebo effect analysis of the post- minus pre-training change scores revealed non-significant paired t-tests for all fatigue test outcome variables, except the initial fatigue response. However, its significance indicated a greater loss of force in the first minute of the fatigue test. General training effect analysis for the training group revealed significant post- minus pre-training change scores for MVIC force and VA regression line slopes, initial fatigue MVIC force and VA response, and predicated force and VA value at minute one. Training group predicted fatigue test end point MVIC force and VA values, total endurance force volume change scores, and total endurance time change scores were not significant. Training efficacy analysis (one-way ANOVA with pre-training value as a covariable) revealed significant between group post- minus pre-training change scores for MVIC force and VA regression line slopes, initial fatigue response, and predicted value at minute one. Control vs. training group predicted end point MVIC force and VA, total endurance force volume change score, and total endurance time were not significant. Recovery Data Analysis: Post-fatigue test recovery group means and standard errors for MVIC force and VA are graphically presented in Figures 3-10 and 3-11, respectively. Numeric values of the recovery MVIC force and VA data are presented in Tables 3-4 and 3-5, respectively. Fatigue test end-point values (RC0) were included in the analysis in order to evaluate the initial recovery phase (RC0-RC1). Pre-fatigue test MVIC force and VA values were also included following the last recovery period (RC20) for general reference purposes. Analysis of pre-training between-groups differences across recovery time was conducted with a two-way ANOVA. No significant force group x time interaction effect ($f= 2.86$, $p= 0.0903$) or group main effect ($f= 2.01$, $p= 0.1816$) was present; however, the time main effect was

significant for both MVIC force (f= 27.77, p= <0.0001) and VA (f=7.56, p= 0.0067) recovery measurements. The placebo effect analysis, conducted using a paired t-test of post- minus pre-training change scores for the control group, revealed no significant placebo effect at any recovery time period for either MVIC force or VA. The general training effect analysis involving paired t-tests of post- minus pre-training change scores, excluding RC0, revealed significant general training effects at all recovery periods for both MVIC force and VA recovery data. Post- minus pre-training group mean recovery change scores for MVIC force and VA are graphically presented in Figures 3-12 and 3-13, respectively. Training efficacy analysis involving two-way ANOVA on MVIC force during recovery revealed a significant group x time interaction effect (f = 3.37, p = 0.0095). Between group follow-up analysis revealed significant non-paired t-tests on MVIC force for all recovery time periods with the exception of RC0 and RC1. Follow-up time analysis on MVIC force for the control group revealed non-significant Bonferroni-adjusted t-tests ($p \geq 0.0911$) for all adjacent time period comparisons. Bonferroni-adjusted t-tests on adjacent time periods for the training group MVIC force showed only one significant comparison, RC0 vs. RC1 (t=3.14, p= 0.0025). Two-way ANOVA on MVIC VA showed a non-significant group by time interaction effect, but significant main group (f= 22.34, p= 0.0006) and time (f= 5.53, p= 0.0003) effects. Follow-up time analysis on MVIC VA for adjacent time periods for both the control and training groups showed only one significant Bonferroni adjusted t-test at RC0 vs. RC1: control group (t= 3.65, p= 0.0005); training group (t= 3.05, p= 0.0034).

Discussion

This study was conducted to examine the effect of high volume voluntary isometric resistance training of the quadriceps femoris on the level of MVIC VA and force development prior to, during, and after a standardized fatigue test protocol. To this end the analysis of the pre-fatigue data revealed a significant general training effect for

the training group in both MVIC VA (pre 78.12%, post 92.26% = 18.10% increase) and force (pre 598.57 N, post 734.95 N = 22.78% increase) from pre- to post-training. This suggests that both central and peripheral training adaptations occurred as a result of the training and that central adaptations may account for the majority of the increase in force. Significant training efficacy for both MVIC VA (control group change score 1.64%, training group change score 14.14%) and force (control group change score 17.93 N, training group change score 136.37 N) was also demonstrated when the training and control groups were compared.

When looking at the fatigue test end-point analysis which indicated no between-group or within-group post- minus pre-training differences, it is interesting to note that we were able to fatigue both groups pre- and post-training to approximately the same level, thus substantiating the long duration (multiple low intensity, 25% MVIC efforts) fatigue test model described by Behm and St. Pierre (1997).

To the best of the author's knowledge, no other study has examined the time course development of central fatigue. We took measures every one minute until the fatigue test end point. On observation of the fatigue test data, a linear relationship was visually apparent between MVIC VA versus time and force versus time, as demonstrated in Figures 3-3 and 3-4. In order to enhance measurement reliability linear regression analysis was used to generate individual subject best fit fatigue regression lines. Using the individual subjects' regression equations we were able to predict with confidence the initial value (one minute of the fatigue task) and final end point value of the fatigue test. The slope of the regression line quantitatively provided a method of assessing the rate of change in fatigue. To the authors best knowledge our study is the first study to utilize this quantitative approach in analyzing central mechanisms of fatigue. Analysis of the effects of training on the early measurements taken during the fatigue test revealed a significantly higher MVIC force and VA level at one minute into the fatigue test. As reflected by the initial fatigue response data it is interesting to note that training

minimized the detrimental fatigue effect during this phase of the fatigue process. The initial fatigue response in the training group showed a MVIC force drop of 88.36 N from pre fatigue to minute one of the fatigue test compared to a 50.61 N drop post-training, MVIC VA dropped 13.89% pre-training and only 0.62% post-training. This suggests that MVIC strength training with a high training volume may have a sparing effect on MVIC force and VA production in the early stages of a fatigue task. Curiously the fatigue test regression line slope analysis indicated a significant increase in the rate of fatigue post training for both MVIC force and VA for the training group. However there was not a significant training effect on total endurance time or total endurance force volume. Therefore, despite the increased rate of fatigue in the training group, it appears they were able to complete the same amount of work in the same period of time by working at a higher force level for the first eight minutes (approximately three-quarters of the fatigue test, Figure 3-7 and Figure 3-8) post-training. Efficacy analysis of post- minus pre-training change scores revealed significant training vs. control group differences for predicted value at one minute of fatigue task, initial fatigue response, and response line slope for MVIC force and VA outcome variables. Efficacy analysis for between group difference in predicted end point, total endurance time, and total endurance force volume were not significant. These later results were not surprising given the non-significant outcome of the training group general training effect analysis of the same outcome variables.

Analysis of the general training effect for recovery measures of MVIC VA and force production revealed that the training group had significantly increased both their MVIC VA and force measures at all recovery time intervals. Efficacy analysis of the between group differences for force with the exception of RC1 comparisons were significant. While analysis of adjacent recovery time intervals for each groups recovery force revealed that the training group had recovered to a significantly greater extent at RC1 post-training than pre-training and even though their force levels continued to

recover as the measures progressed, none of the adjacent time interval comparisons reached significance. Therefore, indicating that the majority of MVIC force post- minus pre-training recovery improvement occurred in the first minute of the recovery period for the training group. Efficacy analysis of the post- minus pre-training between-group differences for MVIC VA, with the exception of RC1 comparisons, were significant. While analysis of adjacent recovery time intervals for each group's recovery MVIC VA revealed that both groups had recovered to a significantly greater extent at RC1 post-training than pre-training. As opposed to force recovery, both the control and training groups achieve statistical significance in the recovery of MVIC VA in the first minute of recovery. As recovery proceeded the training group continued to realize improvements in MVIC VA, although these later adjacent time interval comparisons did not reach statistical significance. From Figures 3-10 and 3-11 it is clear to see that even after twenty minutes of recovery neither MVIC force nor VA had recovered completely. However, a cursory examination of the recovery deficits for each group in both the pre- and post-training states revealed that the training group pre-training force recovery deficit at 20 minutes of recovery as compared to their pre-fatigue value was -12% while post-training this deficit was reduced to -9%, this is in stark contrast to the control group who demonstrated a -8% deficit pre-training and a -13% deficit post-training. For VA we see a similar pattern with the training group pre-training demonstrating a -11% deficit but only a -3% deficit post-training while the control group demonstrates a -9% deficit pre-training and a -15% deficit post-training. This was not part of our statistical analysis, but does lend further support to the notion that training will lead to improvements in recovery.

Conclusions

1. In the non-fatigued state, high force, high volume isometric strength training of the quadriceps femoris leads to adaptations in central mechanisms of MVIC VA and muscle force production allowing greater VA and force production after training.
2. High force, high volume isometric strength training of the quadriceps femoris leads to an increased resistance to the initial phase of fatigue but also increased rate of fatigue resulting in insignificant changes in total force volume and endurance time. This is possibly secondary to training-induced adaptations which minimize the initial fatigue effects on force and VA and the overall increased level of force and VA output displayed through the first two-thirds of the fatigue task.
3. High force, high volume isometric strength training of the quadriceps femoris increased MVIC VA and force output at all recovery time periods. The predominance of the MVIC VA and force recovery adaptations occurred in the first minute of recovery.

Table 3-1. Group demographics (mean ± s.e.).

	Control Group (n=6, 4M:2F)	Training Group (n=8, 3M:5F)
Age (yrs)	23.17±0.7923	23.75±0.8814
Height (cm)	175.90±3.37	176.86±3.84
Weight (kg)	70.31±4.37	71.67±3.42
BMI (kg/m^2)	22.67±1.17	22.98±0.6376
Activity Level	6.79±0.3589	6.58±0.2072

Non-paired t-tests revealed no significant between group differences; age (t= 0.47, p=0.6441), height (t= 0.18, p=0.861, weight (t= 0.31, p=0.761), BMI (t= 0.26, p=0.8014), activity level (t= 0.55, p=0.5944).

Table 3-2. Fatigue test MVIC force (means ± s.e.)

	Control Group			Training Group		
	1	2	3	4	5	6
	Pre Tr Mean(se)	Post Tr Mean(se)	Diff (2-1) Mean(se)	Pre Tr Mean(se)	Post Tr Mean(se)	Diff (5-4) Mean(se)
Pre F (N)	693.05 (54.52)	710.97 (97.01)	17.93 (14.89)	598.57 (40.28)	734.95 (52.28)	136.37 (20.32)
Slope (N/min)	-27.61 (6.82)	-28.10 (6.70)	-0.43 (3.49)	-15.94 (2.36)	-43.34 (7.16)	-27.39 (5.58)
Min 1 (N)	589.08 (63.66)	567.13 (79.54)	-21.94 (24.7)	510.22 (41.33)	684.78 (45.78)	174.57 (24.92)
IFR (N)	103.97 (24.15)	143.84 (30.83)	39.87 (15.34)	88.36 (13.78)	50.16 (11.89)	-38.19 (17.84)
EP (N)	323.52 (48.59)	288.51 (49.13)	-35 (17.39)	290.56 (33.73)	299.9 (27.76)	9.34 (15.98)
Time (min)	805.17 (212.32)	840.17 (243.98)	35 (33.62)	986.38 (205.24)	616.25 (51.66)	-370.13 (185.04)
FV (N min)	115775.89 (20339.73)	117737.33 (20993.82	1961.43 (1381.42	133780.81 (986.38)	102049.24 (6692.94)	-31731.57 (24846.94)

Pre F = pre-fatigue, Slope = slope of fatigue regression line, Min 1 = predicted value at minute one, IFR = initial fatigue response, EP = predicted end point value, Time = fatigue time, FV = fatigue volume.

Table 3-3. Fatigue test MVIC VA (means ± s.e.).

	Control Group			Training Group		
	1	**2**	**3**	**4**	**5**	**6**
	Pre Tr Mean(se)	**Post Tr Mean(se)**	**Diff (2-1) Mean(se)**	**Pre Tr Mean(se)**	**Post Tr Mean(se)**	**Diff (5-4) Mean(se)**
Pre VA (%)	80.44 (2.21)	82.08 (1.48)	1.64 (1.46)	78.12 (3.51)	92.26 (2.12)	14.14 (2.87)
Slope (%/min)	-2.13 (0.69)	-2.03 (0.71)	0.09 (0.25)	-1.53 (0.49)	-4.02 (1.09)	-2.49 (0.82)
Min 1 (%)	60.06 (5.46)	60.24 (2.97)	-0.03 (5.24)	64.23 (4.01)	91.64 (2.27)	27.41 (3.25)
IFR (%)	20.38 (3.31)	22.05 (1.80)	1.67 (3.88)	13.89 (2.59)	0.62 (1.61)	-13.27 (2.7)
EP (%)	36.37 (4.53)	35.54 (6.66)	-0.8 (5.98)	46.27 (5.79)	55.69 (7.12)	9.42 (5.17)

Pre F = pre-fatigue, Min 1 = predicted value at minute one, IFR = initial fatigue response, Slope = slope of fatigue regression line, EP = predicted end point value.

Table 3-4. Recovery MVIC force (means ± s.e.).

	Control Group			Training Group		
	1	2	3	4	5	6
	Pre Tr Mean(se)	Post Tr Mean(se)	Diff (2-1) Mean(se)	Pre Tr Mean(se)	Post Tr Mean(se)	Diff (5-4) Mean(se)
RC0 (N)	323.52 (48.59)	288.51 (49.13)	-35.01 (17.39)	290.56 (33.74)	299.90 (27.60)	9.34 (15.98)
RC1 (N)	517.53 (73.68)	523.12 (87.86)	5.59 (14.75)	415.84 (41.96)	500.38 (34.97)	84.54 (27.01)
RC2 (N)	550.33 (79.03)	526.94 (87.44)	-23.40 (22.94)	410.27 (42.49)	526.50 (40.04)	116.23 (21.90)
RC5 (N)	608.32 (85.75)	576.78 (79.67)	-31.53 (30.00)	457.21 (39.56)	613.29 (49.32)	156.08 (31.22)
RC10 (N)	625.10 (78.83)	618.49 (85.86)	-6.61 (14.29)	488.92 (39.58)	645.41 (51.97)	156.49 (27.60)
RC20 (N)	634.00 (87.42)	617.73 (94.15)	-16.28 (25.71)	528.22 (51.54)	668.14 (56.11)	139.92 (37.38)

Table 3-5. Recovery MVIC VA (means ± s.e.).

	Control Group			Training Group		
	1	2	3	4	5	6
	Pre Tr Mean(se)	Post Tr Mean(se)	Diff (2-1) Mean(se)	Pre Tr Mean(se)	Post Tr Mean(se)	Diff (5-4) Mean(se)
RC0 (%)	36.37 (4.53)	35.54 (6.66)	-0.83 (5.98)	46.27 (5.79)	55.69 (7.12)	9.42 (5.17)
RC1 (%)	64.96 (3.88)	68.55 (6.15)	3.59 (6.04)	61.79 (6.94)	76.26 (3.17)	14.47 (5.19)
RC2 (%)	67.02 (4.58)	63.09 (4.72)	-3.93 (4.99)	60.90 (3.93)	79.37 (3.83)	18.47 (3.81)
RC5 (%)	70.05 (5.25)	67.16 (4.83)	-2.89 (7.03)	61.93 (5.37)	84.15 (2.89)	22.22 (5.45)
RC10 (%)	72.49 (3.74)	68.96 (1.83)	-3.54 (3.98)	65.82 (5.40)	84.89 (1.96)	19.06 (5.16)
RC20 (%)	73.29 (3.43)	71.17 (2.74)	-2.12 (5.82)	69.44 (4.85)	88.77 (0.90)	19.33 (4.76)

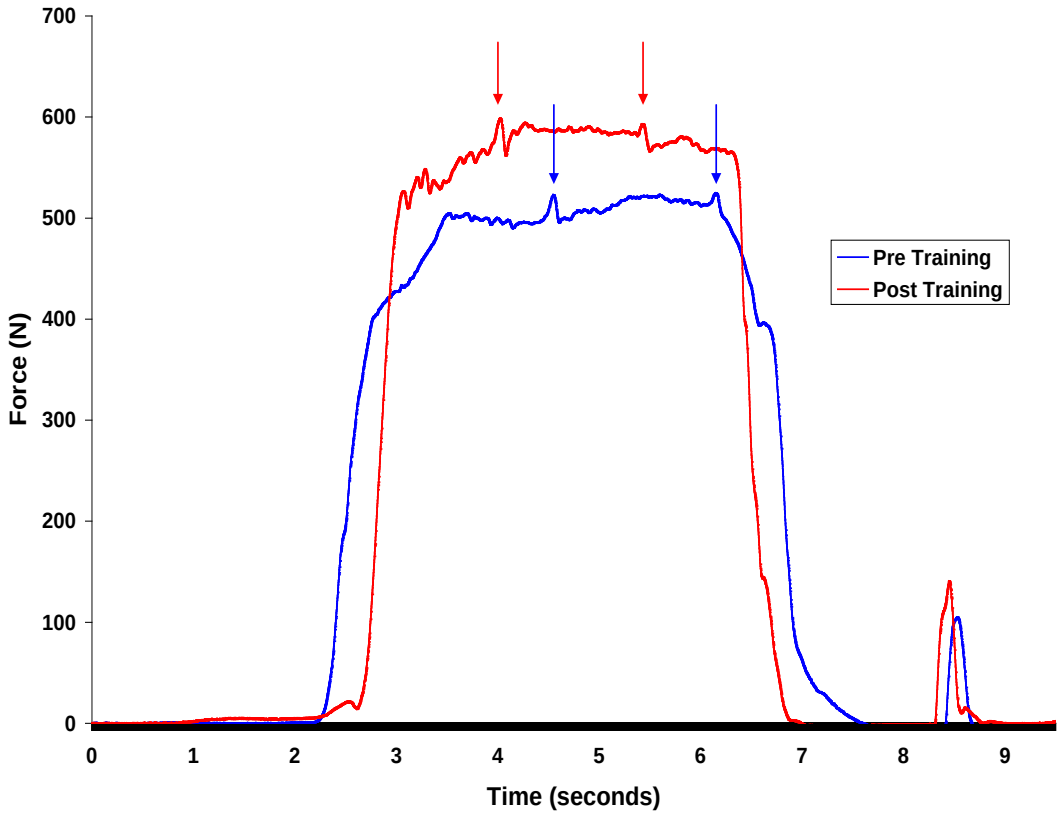


Figure 3-1. Sample ITT measurement.

Note: Arrows mark the point of application of the trains of electrical stimulation superimposed on MVIC force.

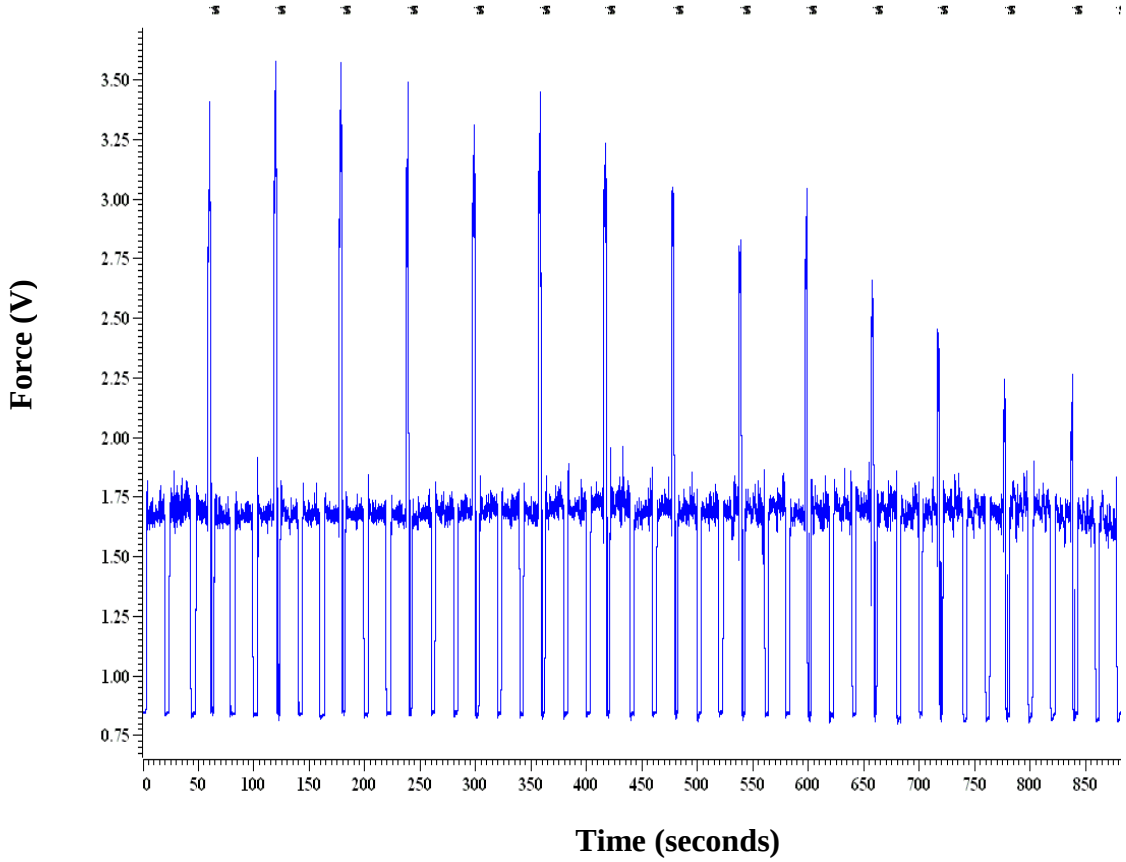


Figure 3-2. Sample fatigue test.

Note: Repetitive stimulation superimposed on brief four second MVICs at one minute intervals throughout the fatigue test. Intermittent fatigue test baseline force equals 25% pre-fatigue MVIC force. Inability to hold the 25% MVIC force for five seconds served as end point criterions.

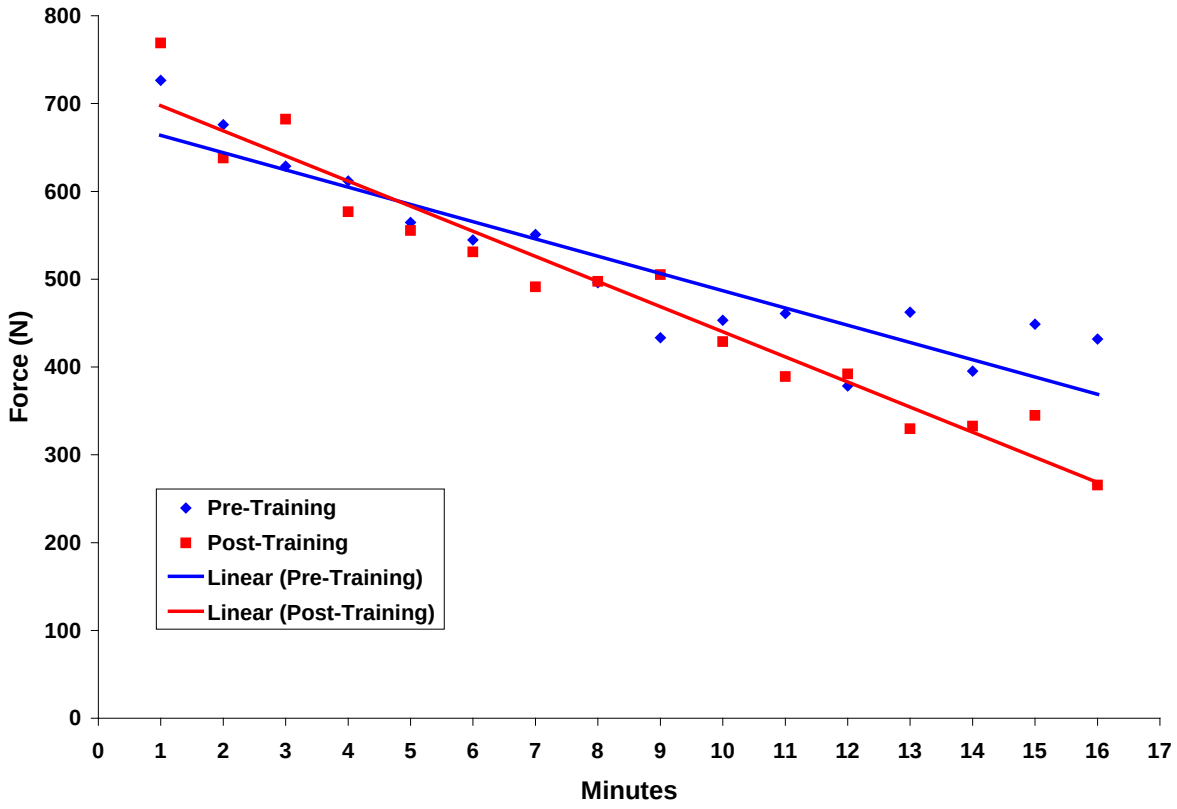


Figure 3-3. Control subject sample fatigue test MVIC force regression line.

Note: Subject regression equations, r^2, and SEE for fatigue regression lines.
Pre-training: y= -19.655x + 683.48; r^2 = 0.8294; SEE = 42.44
Post-training: y = -28.621x + 726.32; r^2 = 0.9439; SEE = 33.22

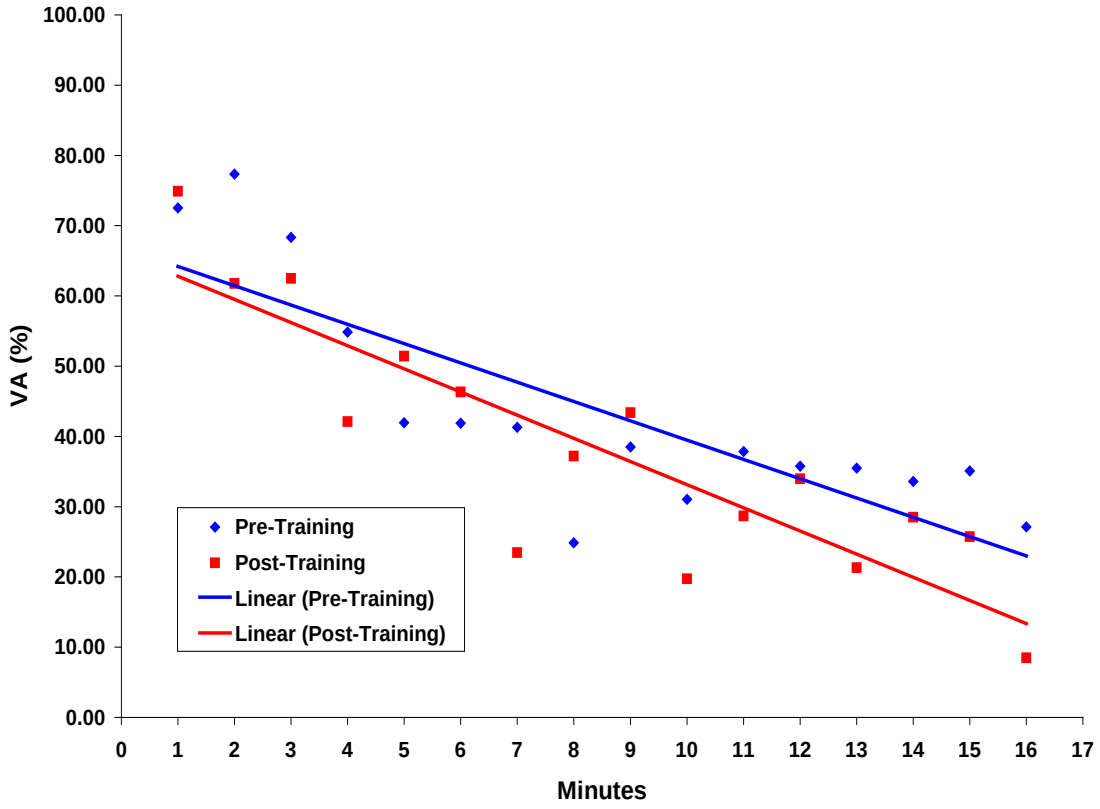


Figure 3-4. Control subject sample fatigue test MVIC VA regression line.

Note: Subject regression equations, r^2, and SEE for fatigue regression lines.
Pre-training: y= -2.7469x + 66.941; r^2 = 0.6636; SEE = 9.31
Post-training: y = -3.2958x + 66.107; r^2 = 0.7597; SEE = 8.82

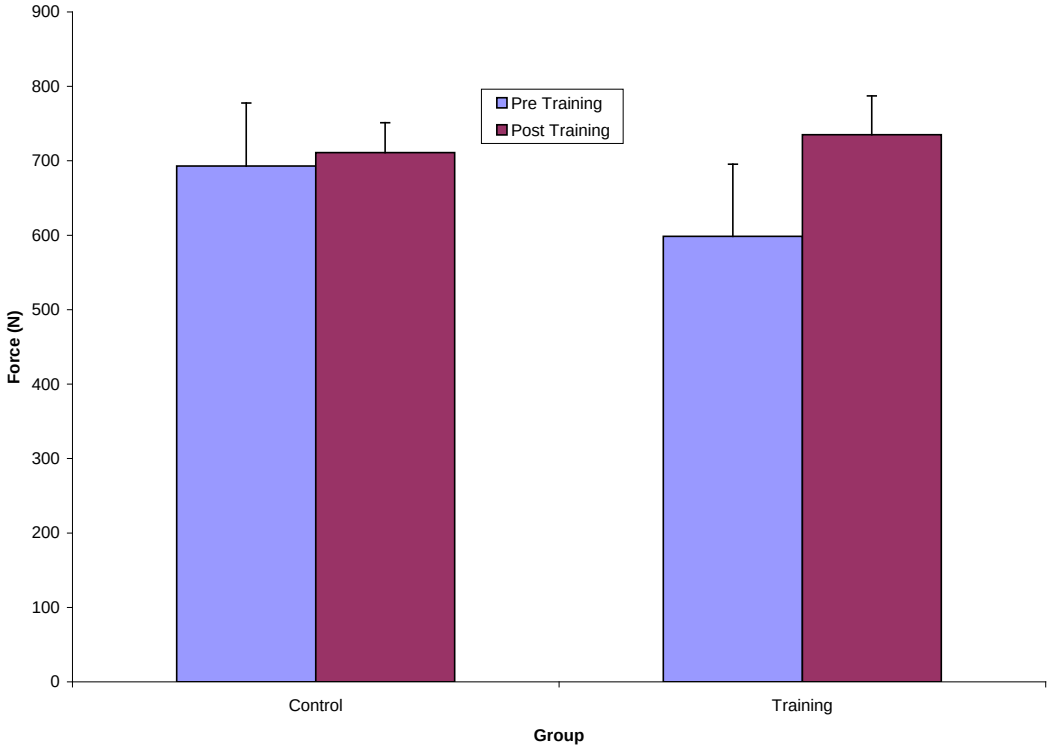


Figure 3-5. Pre-fatigue MVIC force (means ± s.e.)

Note: Pre-Training Analysis: Non-paired t-tests for control vs. training group (t= 1.1, p=0.2942).
Placebo Effect Analysis: Paired t-test of post minus pre-training change score for control group (t= 1.2, p=0.2825).
General Training Effect Analysis: Paired t-test of post minus pre-training change score for training group (t= 6.71, p=0.0003).
Efficacy Analysis: One-way ANOVA of post minus pre-training change score for control vs. training group (f= 28.61, p=0.0002).

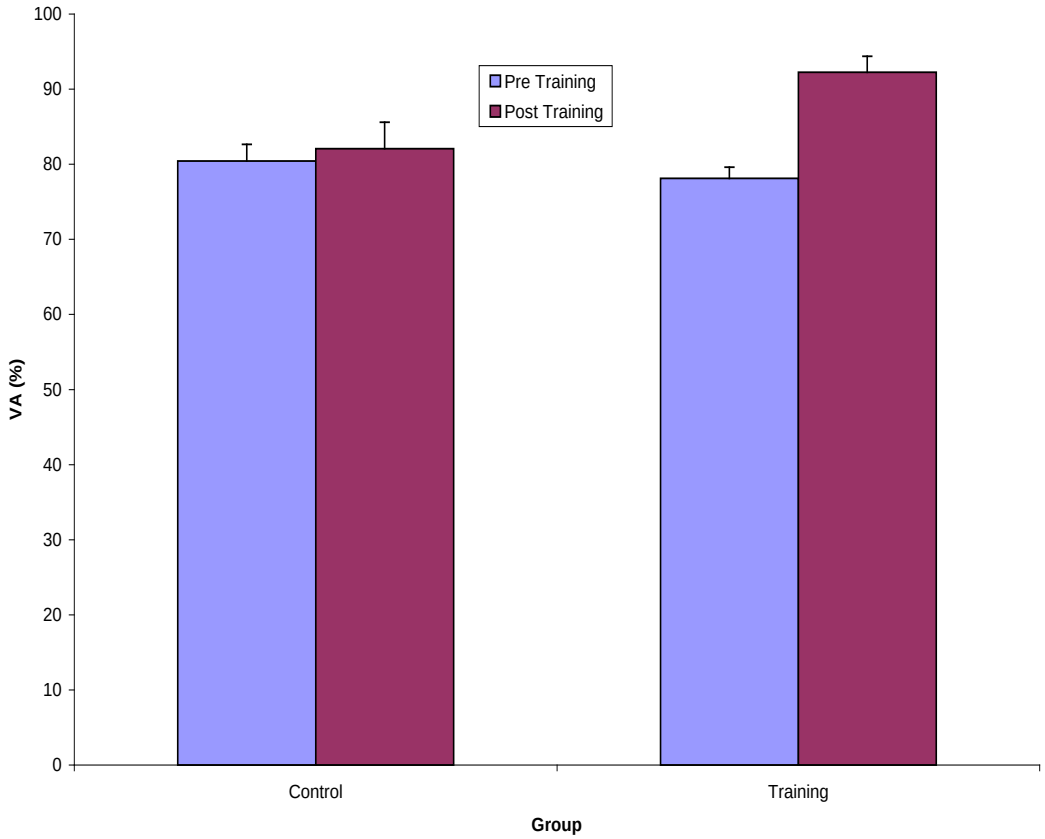


Figure 3-6. Pre-fatigue MVIC VA (means ± s.e.)

Note: Pre-Training Analysis: Non-paired t-tests for control vs. training group (t= 0.51, p= 0.6174).
Placebo Effect Analysis: Paired t-test of post minus pre-training change score for control group (t= 1.12, p=0.3123).
General Training Effect Analysis: Paired t-test of post minus pre-training change score for training group (t= 4.92, p=0.0017).
Efficacy Analysis: One-way ANOVA of post minus pre-training change score for control vs. training group (f= 22.64, p=0.0006).

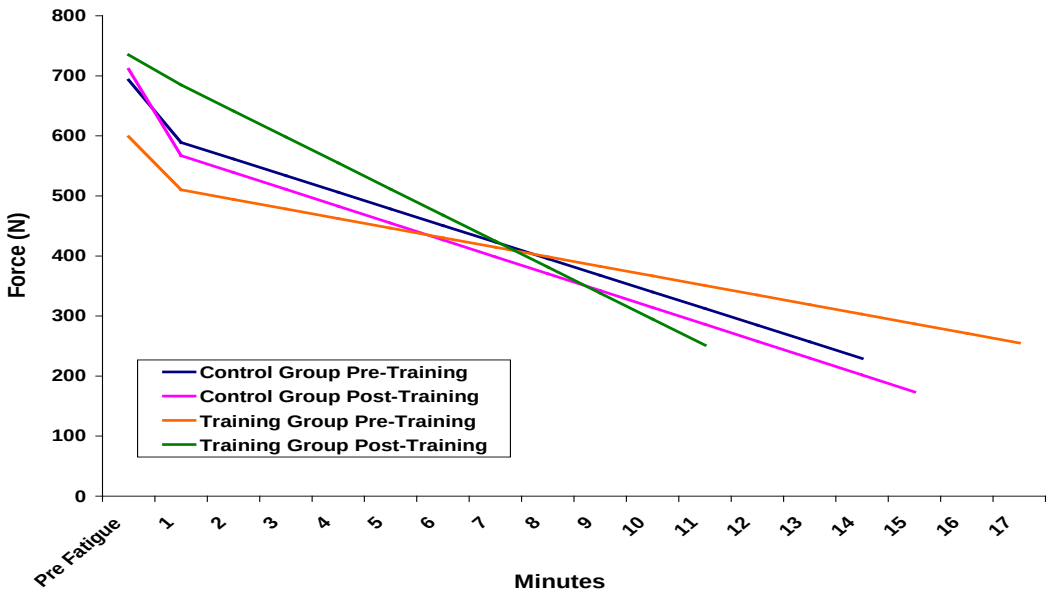


Figure 3-7. Fatigue test MVIC force group mean regression lines.

Note: Pre-Training Analysis: Non-paired t-tests for control vs. training group: slope (t= 1.63, p= 0.1536); initial fatigue response (t=0.6, p= 0.5616); predicted force at minute one (t= 1.09, p= 0.2991); predicted end point force (t= 0.58, p= 0.5751); or total endurance time (min) (t= 0.6, p= 0.5575).
Placebo Effect Analysis: Paired t-test of post minus pre-training change score for control group: slope (t= 0.12, p= 0.9064); initial fatigue response (t= 2.6, p= 0.0483); predicted force at minute one (t= 0.89, p= 0.415); predicted end point force (t= 2.01, p= 0.1003), and total endurance time (min) (t= 1.04, p= 0.3456).
General Training Effect Analysis: Paired t-test of post minus pre-training change score for training group: slope (t= 4.91, p=0.0017); initial fatigue response (t= 2.14, p= 0.0695); predicted force at minute one (t=7.01, p=0.0002); predicted end point force (t=0.58, p=0.5772); and total endurance time (min) (t= 2, p= 0.0856).
Efficacy Analysis: One-way ANOVA of post minus pre-training change score for control vs. training group: slope (f=11.41, p=0.0062); initial fatigue response (f= 11.16, p= 0.0066); predicted force at minute one (f=27.53, p=0.0003); predicted end point force (f=2.81, p=0.1219); and total endurance time (min) (t= 2.15, p= 0.0658).
Mean regression equations (± standard error) for fatigue force response line:
Control Group Pre-Training y = -27.67 (± 6.82)x + 616.75 (± 68.73); SEE = 35.33 (± 5.99), r^2 = 0.86 (± 0.02)
Control Group Post-Training y = -28.10 (±6.70)x + 595.24 (±85.42); SEE = 31.30 (±7.36), r^2 = 0.87 (±0.04)
Training Group Pre-Training y = -15.94 (±2.36)x + 526.16 (±42.34); SEE = 28.73 (±3.90), r^2 = 0.85 (±0.03)
Training Group Post-Training y = -43.34 (±7.16)x + 728.12 (±51.46); SEE = 33.55 (±7.23), r^2 = 0.93 (±0.02)

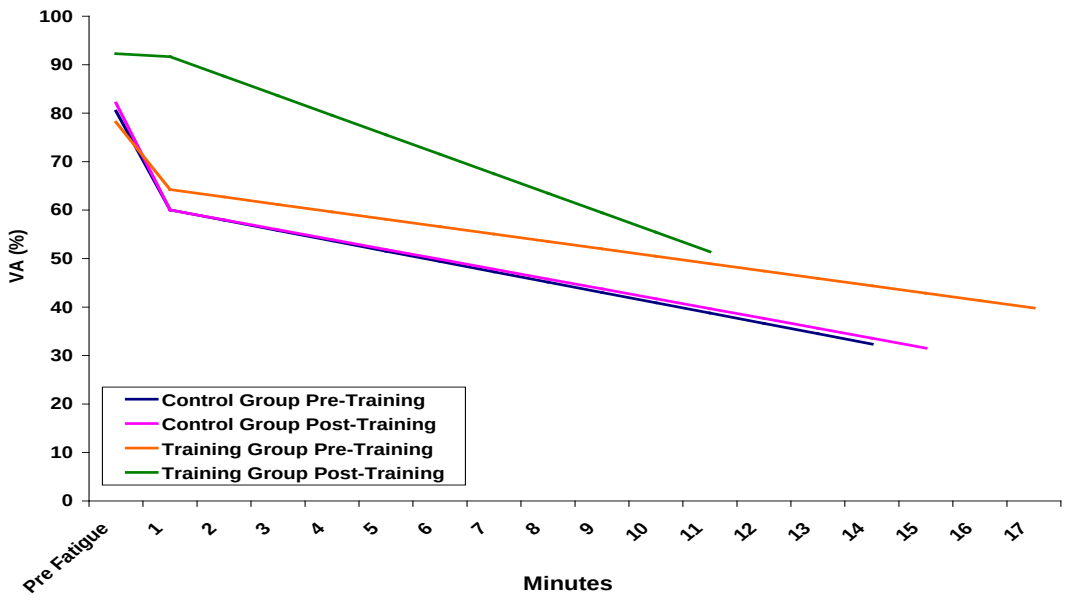


Figure 3-8. Fatigue test MVIC VA group mean regression lines.

Note: Pre-Training Analysis: Non-paired t-tests for control vs. training group: slope (t= 0.74, p= 0.4753); initial fatigue response (t= 1.57, p= 0.1434); predicted VA at minute one (t= 0.63, p= 0.5399); predicted end point VA (t= 1.27, p= 0.2278); and total endurance time (min) (t= 0.6, p= 0.5575).
Placebo Effect Analysis: Paired t-test of post minus pre-training change score for control group: slope (t= 0.39, p= 0.7138); initial fatigue response (t= 0.43, p= 0.6847); predicted VA at minute one (t= 0.01, p= 0.9953); and predicted end point VA (t= 0.14, p= 0.8945); and total endurance time (min) (t= 1.04, p= 0.3456).
General Training Effect Analysis: Paired t-test of post minus pre-training change score for training group: slope (t= 3.06, p=0.0183); initial fatigue response (t= 4.91, p= 0.0017); predicted VA at minute one (t=8.43, p=<0.0001); predicted end point VA (t=1.82, p=0.1113); and total endurance time (min) (t= 2, p= 0.0856).
Efficacy Analysis: One-way ANOVA of post minus pre-training change score for control vs. training group: slope (f=7.41, p=0.0199); initial fatigue response (f= 57.96, p= <0.0001); predicted VA at minute one (f=78.71, p=<0.0001); predicted end point VA (f=1.93, p=0.1918); and total endurance time (t= 2.15, p= 0.0658).
Mean regression equations (± standard error) for fatigue VA response line:
Control Group Pre-Training $y = -2.13\ (\pm 0.69)x + 62.19\ (\pm 5.65)$; SEE = 7.12 (±0.91), $r^2 = 0.53\ (\pm 0.14)$
Control Group Post-Training $y = -2.03\ (\pm 0.71)x + 62.06\ (\pm 3.65)$; SEE = 6.28 (±0.80), $r^2 = 0.52\ (\pm 0.15)$
Training Group Pre-Training $y = -1.52\ (\pm 0.48)x + 65.75\ (\pm 4.01)$; SEE = 7.32 (±0.75), $r^2 = 0.45\ (\pm 0.09)$
Training Group Post-Training $y = -4.02\ (\pm 1.09)x + 95.66\ (\pm 2.63)$; SEE = 6.43 (±1.03), $r^2 = 0.70\ (\pm 0.09)$

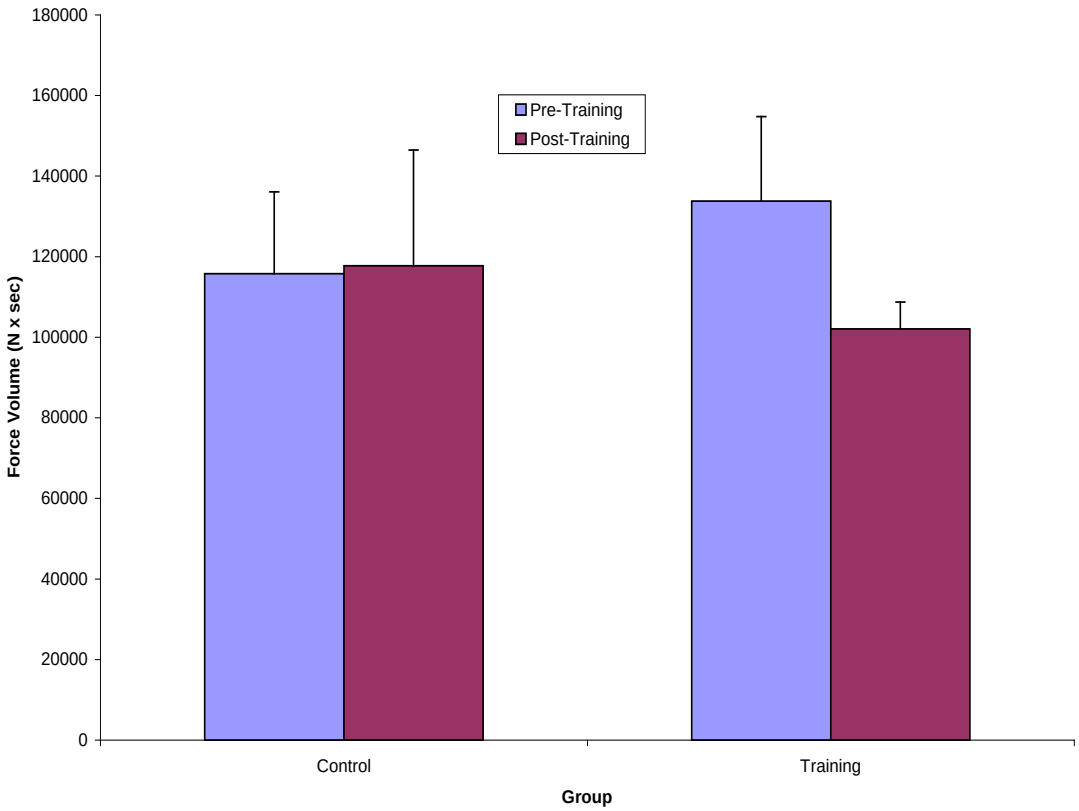


Figure 3-9. Fatigue test total endurance force volume Group (means ± s.e.)

Note: Pre-Training Analysis: Non-paired t-tests for control vs. training group total endurance force volume (t= 0.48, p=0.6421).
Placebo Effect Analysis: Paired t-test of post minus pre-training change score for control group total endurance force volume (t=1.42, p=0.2149).
General Training Effect Analysis: Paired t-test of post minus pre-training change score for training group total endurance force volume (t= 1.28, p=0.2423).
Efficacy Analysis: One-way ANOVA of post minus pre-training change score for control vs. training group total endurance force volume (f=1.96, p=0.1895).

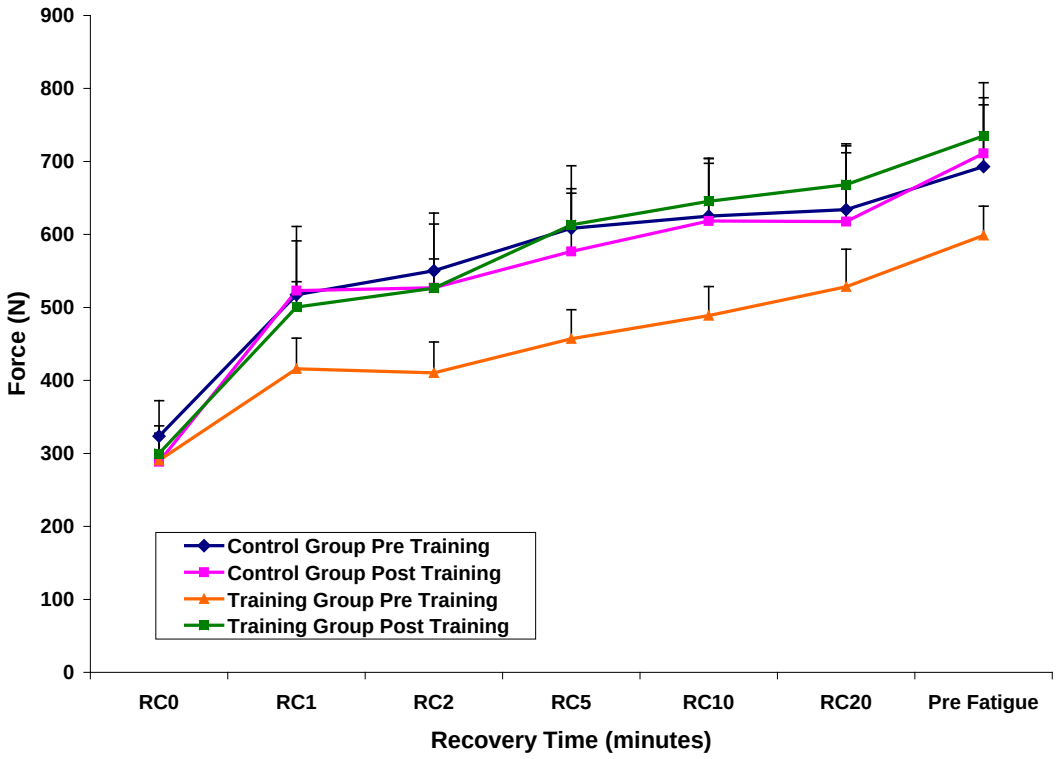


Figure 3-10. Post-fatigue test recovery MVIC force (means ± s.e.)

Note: Pre-Training Analysis: Two-way ANOVA of control vs. training group and recovery time: group x time (f=2.86, p= 0.0903); group (f= 2.01, p= 0.1816); time (f= 27.77, p= <0.0001).
Placebo Effect Analysis: Paired t-test of post minus pre-training change score for control group: RC0 (t= 2.01, p= 0.1003); RC1 (t=0.38, p= 0.72); RC2 (t= 1.02, p=0.3545); RC5 (t= 1.05, p= 0.3414); RC10 (t= 0.46, p= 0.6631); RC20 (t= 0.63, p= 0.5546).
General Training Effect Analysis: Paired t-test of post minus pre-training change score for training group: RC0 (t= 0.58, p= 0.5772); RC1 (t=3.13, p= 0.0166); RC2 (t= 5.31, p=0.0011); RC5 (t= 5, p= 0.0016); RC10 (t= 5.67, p= 0.0008); RC20 (t= 3.74, p= 0.0072).

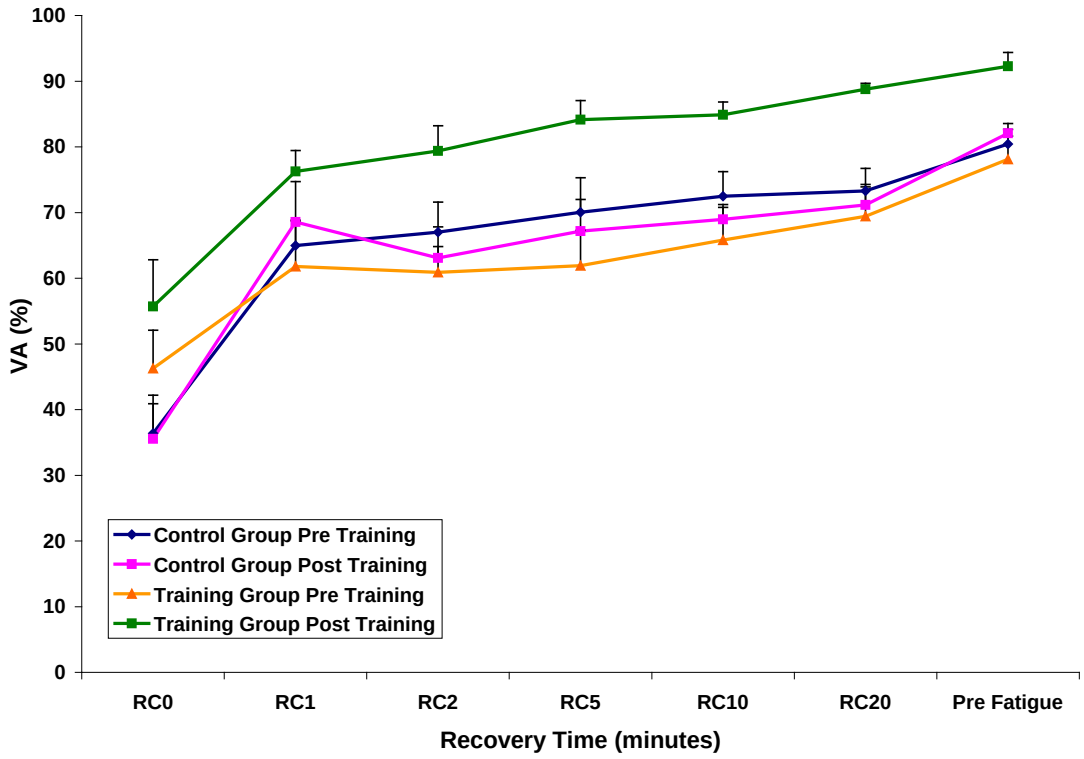


Figure 3-11. Post-fatigue test recovery MVIC VA (means ± s.e.).

Note: Pre-Training Analysis: Two-way ANOVA of control vs. training group and recovery time: group x time (f=0.89, p= 0.5283); group (f=0.26, p= 0.6199); time (f= 7.56, p= 0.0067).
Placebo Effect Analysis: Paired t-test of post minus pre-training change score for control group: RC0 (t= 0.14, p= 0.8945); RC1 (t=0.59, p= 0.5786); RC2 (t= 0.79, p=0.4668); RC5 (t= 0.41, p= 0.6973); RC10 (t= 0.89, p= 0.4155); RC20 (t= 0.36, p= 0.7303).
General Training Effect Analysis: Paired t-test of post minus pre-training change score for training group: RC0 (t= 1.82, p= 0.1113); RC1 (t=2.79, p= 0.0269); RC2 (t= 4.58, p=0.0019); RC5 (t= 4.08, p= 0.0047); RC10 (t= 3.7, p= 0.0077); RC20 (t= 4.06, p= 0.0048).

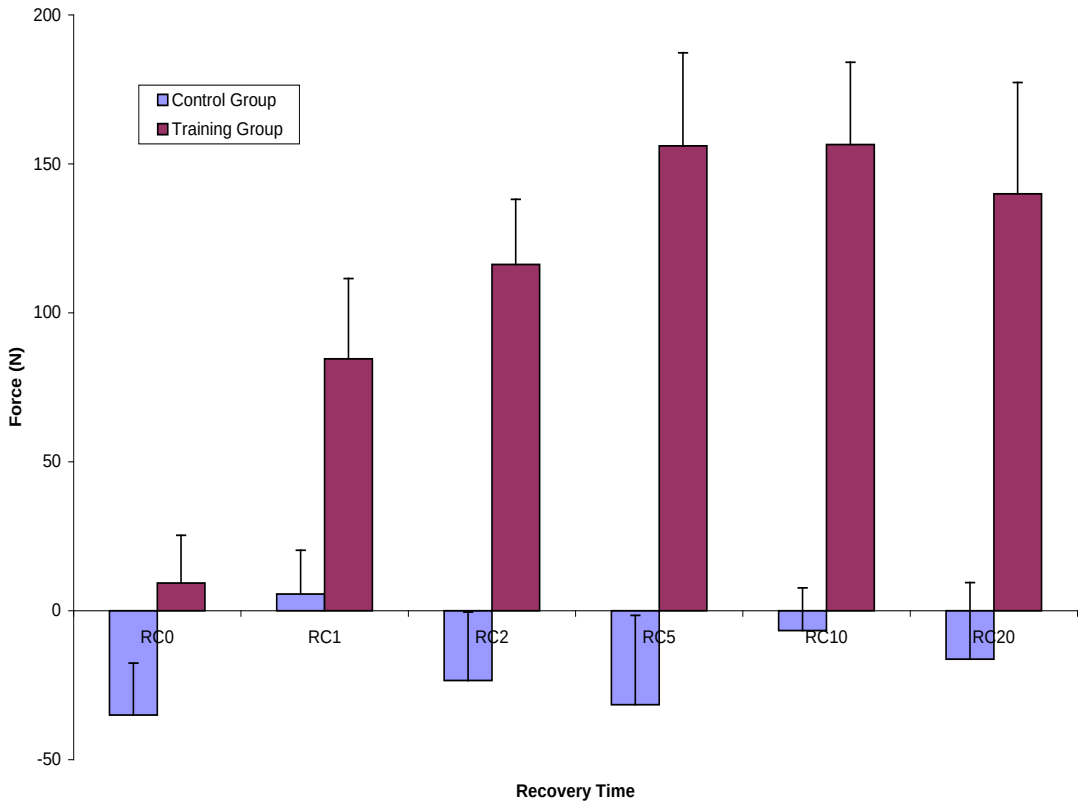


Figure 3-12. Recovery MVIC force post- minus pre-training change scores (means ± s.e.)

Note: Efficacy And Recovery Time Analysis: Two-way ANOVA of post minus pre-training change scores for control vs. training group and recovery time: group x time (f= 3.37, p= 0.0095); group (f= 15.08, p= 0.0022); time (f= 2.94, p= 0.019). Efficacy follow-up analysis of control vs. training group non-paired t-test: RC0 (t= 1.09, p= 0.2861); RC1 (t= 1.79, p= 0.0839); RC2 (t= 3.18, p= 0.0034), RC5 (t= 4.32, p= 0.0002); RC10 (t= 3.78, p= 0.0007); RC20 (t= 3.75, p= 0.0008). Efficacy follow-up analysis of recovery time according to group: Bonferroni adjusted t-tests of adjacent time periods ($\alpha = .05/5 = 0.01$) for the control group revealed no significant differences ($p \geq 0.0911$). Bonferroni adjusted t-tests of adjacent time periods ($\alpha = .05/5 = 0.01$) for the training group revealed: RC0 vs. RC1 (t= 3.14, p= 0.0025), RC1 vs. RC2 (t= 1.24, p= 0.2199), RC2 vs. RC5 (t= 1.73, p= 0.0892), RC5 vs. RC10 (t= 0.13, p= 0.8985), RC10 vs. RC20 (t= 0.51, p= 0.6088).

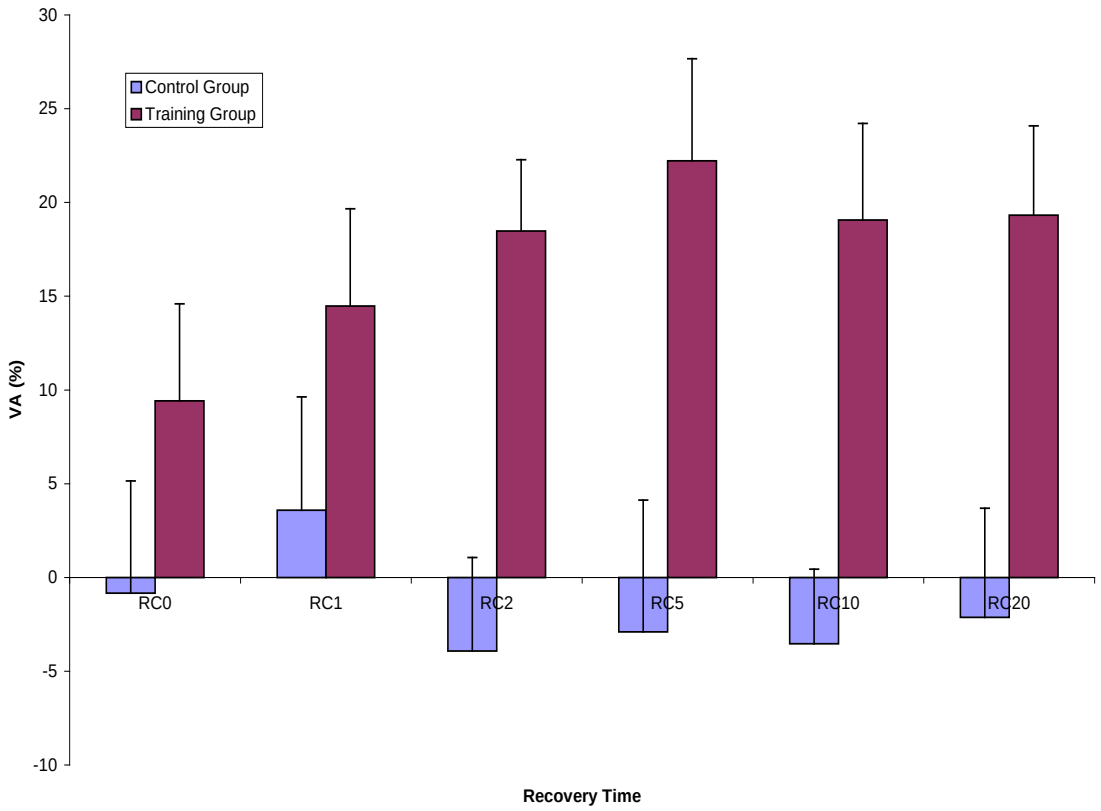


Figure 3-13. Recovery MVIC VA post- minus pre-training change scores (means ± s.e.)

Note: Efficacy and recovery time analysis: Two-way ANOVA of post minus pre-training change scores for control vs. training group and recovery time: group x time (f=0.7, p=0.624); group (f=22.34, p=0.0006; time (f=5.53, p=0.0003). Efficacy follow-up analysis of control vs. training group non-paired t-test: RC0 (t= 2.83, p= 0.0067); RC1 (t= 1.56, p= 0.1251); RC2 (t= 3.24, p= 0.0021), RC5 (t= 3.48, p= 0.001); RC10 (t= 3.21, p= 0.0023); RC20 (t= 3.33, p= 0.0016). Efficacy follow-up analysis of recovery time according to group: Bonferroni adjusted t-tests of adjacent time periods ($\alpha = .05/5 = 0.01$) for the control group revealed: RC0 vs. RC1 (t= 3.65, p= 0.0005), RC1 vs. RC2 (t= 1.2, p= 0.2367), RC2 vs. RC5 (t= 0.56, p= 0.5783), RC5 vs. RC10 (t=0.17, p= 0.8668), RC10 vs. RC20 (t= 0.37, p= 0.7151). Bonferroni adjusted t-tests of adjacent time periods ($\alpha = .05/5 = 0.01$) for the training group revealed: RC0 vs. RC1 (t= 3.05, p= 0.0034), RC1 vs. RC2 (t= 0.76, p= 0.4482), RC2 vs. RC5 (t= 0.97, p= 0.3348), RC5 vs. RC10 (t= 0.16, p= 0.8714), RC10 vs. RC20 (t= 0.55, p= 0.5812).

CHAPTER 4

THE EFFECTS OF RAMPED AND BALLISTIC ISOMETRIC STRENGTH TRAINING OF THE QUADRICEPS FEMORIS ON VOLUNTARY ACTIVATION AND FORCE PRODUCTION.

Introduction

Numerous studies examining the effect of resistance training on maximal muscle strength have been conducted, demonstrating that by and large the adaptations to training are specific to the training mode and parameters utilized (DeLorme 1945; Rasch 1957; Moffroid and Whipple 1970; Thorstensson, Karlsson et al. 1976; Thorstensson 1977; Lesmes, Costill et al. 1978; Lindh 1979; Caiozzo, Perrine et al. 1981; Sargeant, Hoinville et al. 1981; Anderson and Kearney 1982; Rutherford, Greig et al. 1986; Narici, Roi et al. 1989; Stone 1994; Campos, Luecke et al. 2002; Munn J 2005). Recent studies have begun to examine the effect of resistance training on central mechanisms of muscle force production (Jones and Rutherford 1987; Brown AB 1990; Carolan and Cafarelli 1992; Garfinkel and Cafarelli 1992; Herbert, Dean et al. 1998; Hurley and Scott 1998; Harridge, Kryger et al. 1999; Knight and Kamen 2001; Scaglioni, Ferri et al. 2002; Shima, Ishida et al. 2002). The level of voluntary activation (VA) is considered a measure of central mechanisms of muscle force production (Behm and St-Pierre 1997; Stackhouse, Dean et al. 2000; Knight and Kamen 2001). Complete VA is representative of the subject recruiting all motor units and firing them at their optimal rate (Merton 1954; Loscher, Cresswell et al. 1996; Miller, Downham et al. 1999; Stackhouse, Dean et al. 2000; Knight and Kamen 2001; Williams and Bilodeau 2004). The level of VA is commonly assessed using the interpolated twitch technique (ITT) in which a single pulse, doublet or train of supramaximal electrical stimulation is superimposed on the contracting muscle (Merton 1954; Behm, St-Pierre et al. 1996; Miller, Downham et al. 1999; Roos, Rice et al. 1999; Kawakami, Amemiya et al. 2000; Suter and Herzog 2001;

Williams, Sharma et al. 2002; Williams and Bilodeau 2004). If complete VA of the muscle has been achieved, no extra force will be elicited by the superimposed stimulation, however, if all motor units are not recruited and/or are not firing at their optimal rate, additional force will be elicited by the superimposed stimulation. Studies have utilized the ITT to assess the effect of voluntary strength training on the level of VA during a maximum voluntary isometric contraction (MVIC) (Jones and Rutherford 1987; Brown AB 1990; Carolan and Cafarelli 1992; Garfinkel and Cafarelli 1992; Herbert, Dean et al. 1998; Hurley and Scott 1998; Harridge, Kryger et al. 1999; Knight and Kamen 2001; Scaglioni, Ferri et al. 2002; Shima, Ishida et al. 2002). Their results vary considerably, ranging from no change to over a 16% increase in VA. The variable outcomes in these studies could in part be explained by the use of suboptimal training parameters and the lack of control over training velocity.

Complete VA represents a state in which all motor units are recruited and firing at their optimal rate, therefore, it would seem logical to choose training parameters that would ensure recruitment of the entire motor unit pool and drive it to its optimal firing frequency. However, this has not been the case as the training load ranged from 50% to 80% of the one repetition maximum (1RM) in two studies (Harridge, Kryger et al. 1999; Scaglioni, Ferri et al. 2002), to 70%-75% of the 1RM in one study (Shima, Ishida et al. 2002), and 100% of the 1RM (Hurley and Scott 1998; Knight and Kamen 2001) in two studies. All of the studies utilizing 100% of the 1RM as the training load have demonstrated significant improvements in the level of VA post training, while two (Scaglioni, Ferri et al. 2002; Shima, Ishida et al. 2002) of the three studies utilizing submaximal training loads demonstrated significant improvements in the level of VA. Maximal training loads will be utilized in the current study based on demonstrated improvements in the level of VA in all studies utilizing maximal training loads, and the expectation that this level of contraction is needed to ensure complete recruitment of the motor unit pool and drive it optimally (Behm 1995).

Along with utilizing maximal training loads, manipulating training contraction velocity to optimize motor unit recruitment and firing frequencies during training could prove beneficial in maximizing training effects on central mechanisms. In the studies that have assessed the ability of voluntary contraction resistance training to increase the level of VA during a MVIC, none have identified the velocity of contraction utilized in training or testing (Jones and Rutherford 1987; Brown AB 1990; Carolan and Cafarelli 1992; Garfinkel and Cafarelli 1992; Herbert, Dean et al. 1998; Hurley and Scott 1998; Harridge, Kryger et al. 1999; Knight and Kamen 2001; Scaglioni, Ferri et al. 2002; Shima, Ishida et al. 2002). In the continuum of training velocity, the most rapidly performed dynamic movements and isometric contraction velocities are termed ballistic. Ballistic type muscle contractions display several unique characteristics that: 1) make them an optimal model for studying central adaptations to high velocity resistance training and 2) make them an optimal training contraction to induce adaptations in central mechanisms of muscle force production. Ballistic contractions display a characteristic triphasic pattern of agonist/antagonist/agonist muscle activity, with the initial agonist, and potentially antagonist burst being preprogrammed (Garland and Angel 1971; Angel 1975; Hallett, Shahani et al. 1975; Hallett and Marsden 1979). Secondary to the preprogrammed nature of the initial agonist burst, the motor unit discharge is the same whether the involved limb is allowed to move (isotonic contraction) or restrained (isometric contraction) (Desmedt and Godaux 1979). In light of this predetermined motor unit discharge, velocity specific training responses have been demonstrated in isometric ballistic training, with subjects demonstrating the greatest increase in peak torque at the highest isokinetic velocities tested (Behm and Sale 1993). Due to technical challenges, such as movement of the stimulating electrodes and changes in the muscle length-tension relationship it is difficult to perform the ITT during dynamic contractions (Newham, McCarthy et al. 1991). Therefore, the fact that velocity specific training responses are demonstrated in ballistic isometric training makes them an ideal model in

which to study the effect of training velocity on adaptations in central mechanisms of muscle force production. Furthermore, ballistic contractions represent an optimal contraction to maximize motor unit recruitment and firing frequency. Desmedt and Godaux conducted a series of experiments examining motor unit recruitment and firing rate during ballistic contractions of the tibialis anterior (Desmedt and Godaux 1977). They demonstrated that in ballistic contractions of the tibialis anterior: 1) orderly motor unit recruitment is maintained, 2) the force recruitment threshold of individual motor units is decreased by a factor of 0.7, and 3) the initial motor unit firing frequency is increased nearly 6x over firing rates at MVC (Desmedt and Godaux 1977). These findings have been reproduced in the soleus and first dorsal interosseous (Desmedt and Godaux 1978). The present study included a ballistic trained group to take advantage of the lowered motor unit force recruitment threshold and increased motor unit firing frequency in an attempt to maximize the training load placed on larger motor units and optimize training of central adaptations.

When considering information gleaned from studies on velocity-specific training effects several points must be considered. In general, isokinetic training studies have demonstrated the greatest increase in muscle force development at the specific velocity used in training (Moffroid and Whipple 1970; Lesmes, Costill et al. 1978; Caiozzo, Perrine et al. 1981). However, a carryover effect of high velocity training has also been demonstrated (Narici, Roi et al. 1989; Behm and Sale 1993). When low- and high-velocity training groups have been compared, high-velocity training groups have often demonstrated increased muscle force production not only at the training velocity but also at velocities of testing that are lower than the training velocity (Moffroid and Whipple 1970; Lesmes, Costill et al. 1978; Caiozzo, Perrine et al. 1981; Behm and Sale 1993). Because of this carry-over effect we should expect subjects who train at high velocities to show improvements in measures of force production and VA at test velocities which are the same as and slower than their training velocity.

Secondly we must consider the potential for an interaction between the effects of training load and training velocity. Subjects who have been resistance trained with loads greater than 80% of the 1RM have demonstrated a constant improvement of 25% in peak torque across all test velocities with the exception of the highest test velocity where only a 10% improvement was found (Thorstensson, Karlsson et al. 1976; Thorstensson 1977). As demonstrated in these studies, one would expect subjects trained with high loads to demonstrate improvements in force production at test velocities greater than those used in the training which could make it difficult to demonstrate a difference in high load training at low and high velocities. However, a study by Munn, Hancock, and Gandevia (Munn J 2005) provides evidence that a differential effect of training velocity can be demonstrated even when all subjects train using high loads. In this study all subjects trained with a load equivalent to 80% of their one repetition maximum (1RM), while training volume (one set or three sets) and training velocity (fast 140°/s and slow 50°/s) were different for each of the four training groups. All training groups demonstrated increased 1RM strength after training, however, when the data were pooled for contraction velocity, high-speed training resulted in an 11% greater increase in 1RM than lower-speed training. Because it has been demonstrated that a differential effect of high-velocity resistance training can be demonstrated even when all subjects train with high loads it is reasonable to expect a differential training effect of training velocity on central mechanisms of muscle force production, given that these mechanisms contribute to the force increase.

To the author's best knowledge, no study has manipulated training contraction velocity to maximize adaptations in central mechanisms (VA) and muscle force production. Deficits in force production and VA of the quadriceps have been recorded following ACL injury, total knee arthroplasty even after knee contusions (Machner, Pap et al. 2002; Mizner, Stevens et al. 2003) (Hurley, Scott et al. 1997; Manal and Snyder-Mackler 2000) (Lewek, Rudolph et al. 2004) (Jones, Jones et al. 1987; Lewek, Stevens et

al. 2001; Stevens, Mizner et al. 2003; Chmielewski, Stackhouse et al. 2004) (Urbach and Awiszus 2002), and (Urbach, Nebelung et al. 2001). Therefore, identification of the optimal training parameters to induce adaptations in central mechanisms (VA) of force production could have widespread effects in enhancing the effectiveness of resistance training programs to restore muscle performance in rehabilitation and sports settings. The purpose of this study was to examine in healthy young adults the use of high resistance, ramp slow contraction velocity versus ballistic fast contraction velocity type strength training as a means of optimizing central adaptations in MVIC VA and force production in MVIC ramp and MVIC ballistic testing, and at submaximal levels (150 ms). Test specificity and training specificity relative to type of muscle contraction were integral questions of the study. Assessment of submaximal MVIC VA and force training changes was an additional point of interest.

Methods

Research Design: A randomized, controlled, repeated measures design (test condition and training condition) was used to make post- minus pre-training and between group (control, ramp, ballistic) comparisons in MVIC force and VA measures on ramp and ballistic test conditions. Although a randomized control design was used because of the small number of subjects involved in the study, potential bias in the subject group assignment was a concern. Subsequently, between group analysis was done on the subject demographics as well as on pre-training outcome variables. Also, in order to minimize any potential pre-training group differences, post- minus pre-training change scores were utilized for the statistical analysis of all study outcome variables. A control group was utilized to analyze both placebo and training efficacy effects. Ramp and ballistic type muscle contractions were utilized to differentiate the effect of training velocity and the potential advantages of the lowered motor unit recruitment threshold and increased initial motor unit firing rates of ballistic type muscle contractions. The

requirement that all subject groups perform both the ramp and ballistic MVIC tests enabled the analysis for test specificity and training specificity. Overall success of the training programs was evaluated by analyzing the post- minus pre-training changes in MVIC VA and force based on the type of training group test specific test results. In order to examine the time course development of MVIC VA and force, submaximal measurements were taken 150 ms from the onset of the ballistic MVIC test. Due to test design restrictions, submaximal measurements were only performed with the ballistic test. Submaximal MVIC VA and force results could only be evaluated based on overall training changes and could not be subjected to the test specificity and training specificity analysis.

Subjects: Originally twenty-seven healthy subjects were randomly assigned to one of three groups: control (10), ramp training (9), and ballistic training (8). Inclusion criteria included: no history of neuromuscular or cardiovascular disease, no history of pain or injury to the musculoskeletal structures of the lower extremity and torso, ability to achieve at least 75% VA of the quadriceps femoris, and no participation in athletics (intramural, club, or varsity) or a scheduled exercise regime. Based on initial screening of MVIC VA readings two control group subjects were eliminated secondary to being unable to achieve $\geq$75% VA. The final subject count for each group was: control (8), ramp training (9), and ballistic training (8). All training and testing was conducted on the dominant leg, which was determined by the leg they would choose to kick a ball. Subjects' activity level was determined using the Habitual Physical Activity Scale (Baecke, Burema et al. 1982) (Appendix B). See Table 1 for subject characteristics. The study was approved by the University of Iowa Institutional Review Board prior to collecting data. All subjects gave informed consent prior to participating in the study. At a minimum all subjects participated in one familiarization and two testing sessions, with the training groups also participating in eighteen training sessions (6 weeks).

Experimental Set-Up: Subjects were seated in a custom designed chair with their knees and hips flexed to 45° and 85° respectively and the back supported which found in our pilot work (Appendix A) to be the optimal test positions. Stabilization straps were placed around the torso, pelvis, and thigh. The force transducer was anchored perpendicular to the distal tibia at a point 2.5 cm proximal to the medial malleoli. The 45°angle of knee flexion was set such that it represent a tensioned measurement, thus helping to reduce system compliance. Apparatus set-up was recorded to ensure accurate reproduction at test sessions.

Force Measurement: Maximal isometric quadriceps femoris muscle contractions into knee extension and electrically elicited quadriceps femoris contractions were measured using an Interface Model 1210AF-300-B load cell. Resolution of the force measurement system is 0.75 N which represents less than 1% of the control twitches that were elicited. Force was sampled at 1000 Hz and stored on a computer for analysis. An oscilloscope provided continuous visual feedback of the force signal. Force during MVIC efforts and force elicited by electrical stimulation at rest was quantified for both ramp and ballistic contraction tests by measuring the maximum force occurring at any point during the voluntary and elicited contractions. Furthermore, the force level at 150 ms into the ballistic contraction was calculated. Onset of contraction was defined as the point in which the force signal exceeded baseline force by 170 mV (Aagaard, Simonsen et al. 2002). Data were analyzed using Spike 2 v. 3.17 software (Cambridge Electronic Design, Cambridge, England).

ITT Measurement: Supramaximal percutaneous electrical stimulation was delivered to the quadriceps femoris using a Digitimer Model DS7A constant current stimulator. Supramaximal stimulation was demonstrated by the lack of additional increases in evoked force at rest with increasing stimulation intensity. Two stimulating electrodes (38x90 mm) were placed such that the cathode was located over the proximal quadriceps mass and the anode was located over the distal quadriceps. Trains of

electrical stimulation (5 pulses, 0.05 ms duration, at 100 Hz) were utilized. In both ramp and ballistic contractions two trains were superimposed at 1 s intervals once maximal force was achieved during MVIC (Figure 4-1). During ballistic contractions, an additional train of stimulation was delivered to the contracting quadriceps 150 ms after the force level exceeded baseline force by 170 mV (Figure 4-1) (Aagaard, Simonsen et al. 2002). Immediately after both ramp and ballistic MVICs one train of stimulation was delivered at rest. All measures of force (evoked, extra, and ongoing) were normalized to the highest MVIC force for each contraction type (ballistic and ramp) for each subject. Voluntary activation was calculated using the following formula: VA (%) = [1-(interpolated evoked twitch/control evoked twitch)] x 100. Two interpolated trains were delivered to each contraction and therefore two values of VA were calculated for each of the five ballistic and ramp MVIC contractions.

Experimental Procedures:

Subject Warm-Up: Prior to familiarization, test, and training sessions, subjects completed a warm-up to ensure preparedness for MVIC testing/training. Subjects pedaled at 50 rpm/ 100 W on a Monark Ergomedic 818E stationary bicycle for 3 minutes after which they performed one repetition of static stretches for the quadriceps and iliopsoas/rectus femoris which they held for 30 seconds each.

Familiarization Session: All subjects participated in one familiarization session to get accustomed to the electrical stimulation and practice performing ramp and ballistic MVICs. The experimental protocol was described in detail for the familiarization session and unique aspects of testing or training sessions are highlighted in subsequent sections. Upon completing the warm-up subjects were positioned in the custom built chair with stimulating electrodes affixed as outlined above. Subject positioning in the chair was recorded and stimulating electrode placement was measured from bony landmarks to ensure reproduction at subsequent testing sessions (Hakkinen and Komi 1983).

Once positioned, subjects performed five progressively graded quadriceps contractions at a self-selected speed with the fifth contraction being an MVIC. This force level was used to set an initial target for ballistic and ramp contractions. The ballistic target was a cursor on the oscilloscope screen located at warm-up MVIC + 10%, and the ramp target was a trace with a two second diagonal ramp to warm-up MVIC +10% drawn on an overhead transparency secured to the oscilloscope screen. These targets were used to perform ballistic and ramp contractions to ascertain the subject's contraction-specific MVIC force level. During ballistic contractions, subjects were encouraged to relax the quadriceps maximally prior to their ballistic contraction into isometric knee extension which they held for five seconds. To perform ramp contractions subjects followed the two-second trace generated on the oscilloscope after which they held their MVIC for three seconds. The peak force attained at any point in the five-second ballistic hold, or at any point during the three-second hold period of the ramp contraction was measured. If a subject exceeded their contraction-specific target force level, ten percent additional force was added to this MVIC force, and a new target was set on the oscilloscope. Ramp and ballistic contractions were repeated in a balanced and alternating manner until the subject was unable to achieve additional force (usually within two to three contractions). These force levels, measured for both ballistic and ramp contractions, were used as the contraction specific target forces for test contractions. When performing MVIC efforts, subjects were provided with loud verbal encouragement and received real-time visual feedback of their performance (Gandevia 2001; Shield and Zhou 2004). The gain of real-time visual feedback was varied from one MVIC to the next (Gandevia 2001). After determining the contraction-specific target forces supramaximal stimulator intensity was set as previously described. Three minutes of rest was given after setting stimulator intensity. Each subject then performed eight MVIC test contractions (four ballistic and four ramp, in a balanced order) with superimposed stimuli to assess VA. Three minutes rest was given between contractions to minimize fatigue. During both the ramp and

ballistic contractions, once the subject had reached MVIC (visually determined) two trains of stimuli were delivered one second apart to test for a maximal contraction. Immediately after each MVIC, a train of stimulation was delivered to the muscle at rest to elicit control trains. Subjects were instructed to attempt to exceed their target force in all contractions. If a subject exceeded the target force levels on any test contraction a new target, based on the measured force, was generated and used in subsequent contractions. This completed the familiarization session.

Testing Sessions: All subjects participated in initial and final test sessions which were separated by six weeks. The training groups performed their assigned training program and all groups were instructed to maintain their habitual level of physical activity during the intervening six weeks. Subject set up and stimulating electrode placement were reproduced using measures from the familiarization session (Hakkinen and Komi 1983). Target MVIC force levels for ramp and ballistic contractions were determined exactly as in the familiarization session and stimulator intensity was set as outlined above. After determining the contraction-specific target forces, subjects were asked to perform a knee flexion MVIC which was recorded and stored for later analysis.

Each subject then perform ten MVIC contractions (five ballistic and five ramp, in a balanced order) of their quadriceps, with three minutes rest between contractions. Subjects were instructed to attempt to exceed their target force in all test contracts. If a subject exceeded the target force level on any test contraction, a new target, based on the measured force, was generated and used in subsequent contractions. Electrical stimulation was applied as outlined in the familiarization session.

Training: Training commenced no less than two and no more than four days after the initial test and was conducted 3x/week for six weeks (18 training sessions). Each training session proceeded as follows: 1) subjects completed the warm-up, 2) subjects were positioned in the testing/training apparatus, 3) subjects target MVIC force level for the respective contraction they are training with (ramp or ballistic) were determined and

the target was set for their training contractions (in this manner the subjects training target was adjusted prior to each set throughout their course of training), 4) subjects then performed their respective training contractions. See Table 4-2 for weekly training load, volume, and rest intervals. Ramp training contractions consisted of a two-second ramp to maximum force followed by a three-second hold at MVIC, while ballistic training contractions consisted of a MVIC performed as explosively as possible and held for five seconds. Based on this performance time construct, fast velocity ballistic type muscle contractions were ~7 times (2 sec/300 ms = 6.6) faster than slow velocity ramp type muscle contractions. Subjects were instructed to attempt to exceed their target force in all training contractions. If a subject exceeded the target force level on any training contraction a new target, based on the measured force, was generated and used in subsequent sets. Upon completion of training, all groups underwent post-training testing, which occurred between two and four days after their last training session. Control subjects were tested six weeks after their initial test. Figure 4-2 shows the daily training log of group mean force level achieved at each training session. As indicated in Figure 4-2 group compliance with training was 100% for the ramp training group and 95.1% for the ballistic training group.

Data Analysis:

Variables Of Interest: The dependent variables of interest common to both ramp and ballistic test contractions were: MVIC force and VA. At 150 ms into the ballistic contractions additional variables of interest included mean force and VA, termed 150 ms Force and 150 ms VA, respectively. The variables were quantified prior to and after training and were compared pre- to post-training within and between groups and test types.

Preliminary Data Processing: Analysis of test data for MVIC force was based on the mean of the top three force generating contractions for both ramp and ballistic test

conditions for individual subjects. Mean VA was computed from the mean of the two superimposed twitches from the three top MVIC force contractions for individual subjects. Mean force and mean VA for the ballistic test submaximal 150 ms test trials were calculated from the corresponding top three force trials for the MVIC ballistic test.

Statistical Analysis: Descriptive statistics (group means and standard deviations for age, height, weight, BMI, and activity level) were calculated and one-way ANOVA was utilized to examine between group differences. Primary outcome variables analyzed at MVIC included force and VA for ramp and ballistic test conditions, and force and VA for the submaximal 150 ms ballistic test condition. Statistical significance of an α level = 0.05 was used for all ANOVA analyses. Bonferroni-adjusted α levels were used for follow-up analyses. Pre-training data were analyzed to assess any potential between group differences associated with subject assignment. Accordingly, a two-factor mixed model with three levels of group (control, ramp, ballistic) and two levels of test (ballistic and ramp) was used to analyze the pre-training MVIC force and VA data. Bonferroni-adjusted t-tests were used to make pairwise contrasts of the between group differences according to the test condition ($\alpha = 0.05/6 = .0083$). One-way ANOVA with three levels of group (control, ramp, ballistic) was used to analyze pre-training 150 ms ballistic test data for force and VA. Bonferroni-adjusted t-tests were used to make pairwise contrasts of the between group differences according on the ballistic test condition ($\alpha = 0.05/3 = .0166$). Change scores (post-pre training differences) were used for the primary test questions: placebo effect, general training effect, training efficacy, training specificity, and test-training specificity analyses. The rationale for using post- minus pre-training change scores was to minimize the potential confounding effects of any pre-training group bias due to chance variation in initial subject group assignment. In addition, the pre-training data were utilized as covariables in all ANOVA analyses of force. . Initial attempts at using pre-training data as a covariable in the ANOVA analysis of VA resulted in non-significant f-tests for all VA analyses. Subsequently, pre-training covariable data

were not used in the ANOVA for VA. A possible explanation for these results may be related to the empirical finding of a high negative correlation between pre-training VA and post- minus pre-training change scores for VA ($r \geq -0.91$). In this context, when pre-training VA was used as a covariable the ANOVA model negated all positive post- minus pre-training effects. Evaluation of the placebo (control group) and general training (ramp and ballistic training groups) effects was accomplished with paired t-tests with an α level = 0.05. To examine training efficacy (control group vs. ramp-trained group and ballistic-trained group) two-way ANOVA with three levels of group (control, ramp, ballistic) and two levels of test condition (ramp and ballistic) was used to analyze MVIC force and VA test data. One-way ANOVA with three levels according to group (control, ramp and ballistic groups) was used for the 150 ms ballistic force and VA test data. Bonferroni-adjusted t-tests were used for making pairwise contrasts between the control group and the ramp and ballistic training groups according to the respective ramp and ballistic test conditions. Examination of training specificity (ramp training group vs. ballistic training group) was accomplished using two-way ANOVA with two levels according to training group (ramp and ballistic) and two levels of test condition (ramp and ballistic) for the MVIC force and VA data, and one-way ANOVA with two levels according to training group (ramp and ballistic) was used to analyze the 150 ms ballistic test force and VA data. Bonferroni adjusted t-tests were used for making pairwise contrasts between ramp and ballistic training groups according to the two specific ramp and ballistic tests. Paired t-tests were used for pairwise within group between test comparisons (ramp group, ramp test vs. ballistic test, and ballistic group, ramp test vs. ballistic test) to analyze the question of test-training specificity.

Results

Subject Characteristics: Group descriptive statistics are included in Table 1. The analysis of subject demographics revealed no significant between group differences for age, height, weight, BMI, and activity level.

Pre-Training Analysis: Group means and standard errors according to test condition for the pre and post-training MVIC force and VA data are graphically presented in Figure 4-3 and 4-4, respectively. Numeric data are presented in Table 4-3 and 4-4. ANOVA of pre-training MVIC force and VA data revealed no significant interaction or main effects for force (group f=3.24, p=0.0605, test f=1.47, p=0.239, group x test, f=1.78, p=0.194) or VA (group f=1.35, p=0.2821, test f=3.87, p=0.0631, group x test, f=2.78, p=0.0859). Bonferroni adjusted t-tests (α= .05/6, p=0.008) showed non-significant pre-training between groups pairwise contrasts for force (Figure 3, $p \geq 0.0217$) and mean VA (Figure 4, $p \geq 0.0355$). Group means and standard errors for the pre and post-training 150 ms force and VA ballistic test results are graphically presented in Figure 4-5 and 4-6 respectively. Numeric data are presented in Table 4-4. One-way ANOVA of pre-training 150 ms force and VA revealed a significant difference between groups for force (f=3.86, p=0.0383) but no significant difference between groups for mean VA (f=1.42, p=0.265) pre training. Bonferroni adjusted t-tests (α = .05/3, p=0.0166) showed non-significant pre-training between groups pairwise contrasts for 150 ms force (Figure 5, $p \geq 0.0515$) and VA (Figure 6, $p \geq 0.3569$).

Group means and standard errors according to test condition for the post- minus pre-training change scores for MVIC force and VA are graphically presented in Figure 4-7 and 4-8, respectively. Furthermore, group means and standard errors for the post-minus pre-training change scores for 150 ms ballistic test force and VA are graphically presented in Figure 4-9 and 4-10, respectively.

Analysis of the control group for the presence of a placebo effect revealed a significant post- minus pre-training change score for mean VA at both MVIC (p=0.0182,

t=3.45) (Figure 4-8) and 150 ms (p=0.0411, t=2.73) (Figure 4-10) of the ballistic test. However, the direction of the pre- to post-test change score was negative. In the ballistic test MVIC mean VA dropped from a pre-test value of 86.95% to 79.95%, and mean VA at 150 ms dropped from a mean pre-test value of 42.63% to a post-test value of 36.09%. No other comparisons for the control group reached statistical significance.

Analysis of the two training groups for general training effects using paired t-tests revealed significant changes from pre- to post-training for both training groups in both test conditions for both MVIC force and VA (Figure 4-7 and 4-8, respectively, ramp group p= 0.0008 to 0.0036, ballistic group p= 0.001 to 0.0461). At 150 ms of the ballistic test the ballistic trained group demonstrated a significant paired difference from pre- to post-training for both force (Figure 4-9, p=0.0074) and VA (Figure 4-10, p=0.0096), while the ramp group change scores did not reach statistical significance for either force (Figure 4-9, p=0.1067) or VA (Figure 4-10, p=0.2855).

Comparison of the control group post-pre training change scores to each training groups post-pre training change scores with two-way ANOVA to examine training efficacy for MVIC force revealed significant interaction (f=4.60, p=0.023), and main effect for group (f=8.07, p=0.0028), but not test (f=0.02, p=0.902). The same analysis for MVIC VA revealed significant interaction (f=7.62, p=0.0035), and main effect for group (f=14.42, p=0.0001), but not test (f=0.34, p=0.566). Bonferroni adjusted t-tests (α=.05/4, p=0.0125) for pairwise comparisons of the control group vs. each training group on each test condition were all significant for MVIC force (Figure 4-7, p= 0.0006 to 0.0076) and MVIC VA (Figure 4-8**,** p<0.0001 to 0.0059). One-way ANOVA comparing control group post- minus pre-training change scores to each training groups post- minus pre-training change scores at 150 ms of the ballistic contraction revealed a significant difference between the control group and the training groups for force (f=7.27, p=0.0045), and mean VA (f=8.39, p=0.0023), as displayed in Figures 4-9 and 4-10 respectively. Bonferroni adjusted t-tests (α=.05/2, p=0.025) for pairwise comparisons of

the control group vs. each training group at 150 ms of the ballistic contraction showed significant differences between the ballistic training group and the control group ($p=0.004$) for force (Figure 4-9) and between the ballistic training group and the control group for mean VA (Figure 4-10, $p=0.0018$)).

Comparison of the two training groups post-pre training change scores with two-way ANOVA to examine training specificity at MVIC significant interaction was found for force ($f=7.43$, $p=0.0156$), but no main effects were found for group ($f=1.14$, $p=0.3012$) or test ($f=0.08$, $p=0.7838$). The same comparison for mean VA revealed a significant interaction effect ($f=4.95$, $p=0.0419$) and test main effect ($f=8.81$, $p=0.0096$), with no group main effect ($f=0.58$, $p=0.4588$). Bonferroni adjusted t-tests ($\alpha=0.05/3$, $p=0.017$) for pairwise comparisons of the ramp vs. ballistic group on the ramp test ($t = 0.69$, $p=0.4965$), ramp vs. ballistic group on the ballistic test ($t=1.43$, $p=0.1706$), and ramp group on the ramp test vs. ballistic group on the ballistic test ($t=1.11$, $p=0.2817$) for MVIC force were non-significant. Furthermore, the same comparisons for MVIC mean VA were non-significant for the ramp test ($t =1.29$, $p=0.2129$), the ballistic test ($t =0.18$, $p=0.8611$), and ramp group on the ramp test vs. ballistic group on the ballistic test ($t=0.01$, $p=0.9929$). Comparison of post-pre training change scores for the ramp and ballistic training group at 150 ms revealed a significant between group difference for force ($f=8.33$, $p=0.0113$) and a non-significant between group difference for VA ($f=4.47$, $p=0.0516$).

Test-Training Specificity Analysis: Paired t-test comparing the ramp group on the ramp test vs. the ballistic test for MVIC force was non-significant ($t=1.64$, $p=0.1217$) while the same comparison for the ballistic group was significance ($t=2.42$, $p=0.0284$). Paired t-tests comparing the ramp group on the ramp test vs. the ballistic test for MVIC VA was non-significant ($t= 0.54$, $p=0.5956$) while the same comparison for the ballistic group was significant ($t=3.57$, $p=0.0028$).

Discussion

The purpose of this study was to examine the use of high resistance, ramp vs. ballistic type muscle contraction strength training as a means of optimizing central adaptations in MVIC VA and force production in MVIC ramp and ballistic tests and at submaximal levels (150 ms into the MVIC ballistic test). Test specificity and training specificity relative to type of muscle contraction were integral questions of the study.

The composite group mean VA for all of our subjects combined pre-training was 89.83% and comparison of this value with those reported in the literature we see that pre-training our sample is very similar. In 2002, while studying VA of the quadriceps femoris in healthy subjects, Behm and colleagues reported an inactivation ratio of 15.5% (VA = 84.5%) in their sample (Behm, Whittle, Button, Powers 2002). Numerous other studies have reported very similar values in healthy subjects demonstrating that complete activation of the quadriceps femoris is infrequently achieved (Becker and Awiszus 2001; Behm and St.Pierre 1997; Hurley, Reese, and Newham 1998; Roos, Rice, Connelly, Vandervoort 1999; Stackhouse, Dean, Lee, Binder-Macleod 2000; Stackhouse, Stevens, Johnson, Snyder-Mackler, Binder-Macleod 2001).

With training, we were able to induce significant adaptations in force development in both training groups at MVIC during both ramp and ballistic tests and in the ballistic training group at the ballistic test 150 ms submaximal measure. In MVIC ramp test conditions the ramp training group experienced a 20% increase in force production while the ballistic training group experienced only a 15.65% increase. In MVIC ballistic test conditions the scenario was just reversed with the ramp training group demonstrating a 17.83% increase in force output while the ballistic training group experienced an 18.88% increase in force output. These results suggest training specificity however, the between group differences were not statistically significant. At the ballistic test 150 ms submaximal measure the ballistic training group achieved a significant increase in force output of 48.76% while the ramp training group only

achieved a 14.29% increase which did not reach significance. This finding supports the tenet of training specificity for the ballistic group. Training adaptations in the level of VA achieved followed a similar pattern with significant adaptations induced by training for both groups at MVIC during both ramp and ballistic tests and in the ballistic training group at the ballistic test 150 ms submaximal measure. In MVIC ramp test conditions, the ramp training group demonstrated a 7.73% increase in VA while the ballistic training group only showed a 4.09% increase. In MVIC ballistic test conditions the groups followed the same pattern, with the ramp training group demonstrating 8.39% increase and the ballistic training group showing a 7.85% increase. At the ballistic test 150 ms submaximal measure the ballistic training group achieved a significant increase in VA output of 31.56% while the ramp training group only achieved a 9.82% increase which did not reach statistical significance ($p= 0.0516$). Comparison of our results to those reported in the literature are difficult secondary to the fact that most studies examining training induced adaptations in VA have not controlled and/or reported training velocity or they have utilized training loads significantly lower than ours. Also, to the author's best knowledge, no other training study has assessed submaximal force and VA levels during the initial phase of MVIC ballistic test (150 ms from contraction onset), therefore there are no studies to which we can compare that portion of our data. It is important to note that we utilized a control group which allowed us to assess training efficacy: "the benefit of an intervention as tested under controlled experimental conditions, usually with a control group" as defined by Portney and Watkins (Portney and Watkins 1999). Again, this has not been the standard in studies examining the effect of training on levels of VA. Both training groups demonstrated significant training efficacy in both MVIC ramp and ballistic tests for force and VA. However, only the ballistic training group demonstrated training efficacy at the ballistic test 150 ms measurement for both force and VA.

Through the years, studies have consistently demonstrated that resistance training leads to increases in force output and in some studies training specificity has been

demonstrated with regard to training load and training velocity. Studies in which a training load greater than 80% of the subject's one repetition maximum (1RM) was used have demonstrated improvements in torque production across all test velocities of about 25% with the exception the highest test velocity where only a 10% improvement was demonstrated (Thorstensson, Karlsson et al. 1976; Thorstensson 1977). Thus subjects trained with high loads certainly experience the greatest increase in force production at the lower test velocities, but a carry-over effect to higher test velocities still occurs and improvement is seen even at the highest test velocities. Likewise, subjects trained with high velocity contractions have demonstrated the greatest increase in force production at the highest test velocities, but also have shown the carry-over effect to slower testing velocities (Narici, Roi et al. 1989; Behm and Sale 1993). Despite the potential for interaction of the effects of our high load and high velocity training program we were optimistic that contraction velocity-specific training adaptations could be demonstrated based on the work of Munn and colleagues, 2005 (Munn J 2005). As illustrated in Figure 4-7 the post- minus pre-training change scores on the ramp test were comparable for both training groups. In contrast, the post- minus pre-training change score for the ballistic group on the ballistic test was greater than both the ramp and ballistic tests for the ramp group. Although these trends suggest potential benefits of high contraction velocity training, the observed differences were not statistically significant as indicated in our training specificity analysis. For VA, as seen in Figure 4-8, the greater post- minus pre-training change scores for the ramp group on the ramp test as compared to the ballistic group suggests potential training specificity, however, none of these comparisons was statistically significant.

When examining the effect of training contraction type (ramp or ballistic) on ramp and ballistic test conditions it is important to note that the ballistic training group demonstrated significantly better performance on the MVIC ballistic test for both force and VA, while the ramp training group showed no difference. Therefore, to control for

potential confounding effects of test-training velocity specificity, researchers should be cognizant of the need to match training and testing velocity.

As indicated earlier, submaximal measures of force and VA have to the author's best knowledge not been utilized. However, intuitively they may represent a more important "functional" measure of both force and VA production than do maximal level measurements. It was already noted that 100% VA has been infrequently reported in the literature, which is not surprising as most subjects would rarely have a need to achieve 100% activation in their normal daily lives. Thus, a state of 100% activation would be novel. However, the rate at which we can recruit motor units and get them maximally firing to produce force quickly may be a more "functional" measure. When a joint or the whole body experiences a perturbation with resultant malalignment and instability, muscles, through their production of force, are called upon to restore alignment and stability. Often these perturbations are applied rapidly and at times unexpectedly requiring acute force production to stabilize. Numerous examples exist from someone trying to catch themselves to prevent a fall or an athlete's trying to overcome the constantly varying perturbations they experience from their opponent and playing surfaces. It is very interesting to note that in our study only the ballistic training group demonstrated significant general training effects and training efficacy for the VA and force measures at 150 ms of the ballistic test contraction. Furthermore, significant training specificity was demonstrated for force production, and borderline significant specificity was demonstrated ($p=0.0516$) for VA. Training interventions aiming to increase the rate at which muscle force and VA can be generated should incorporate high velocity training strategies.

At the mechanistic level, this study clearly links adaptations in central mechanisms of force production to increases in force output. Both ramp and ballistic training at high force levels (MVIC) were able to induce these adaptations during the high force tests, but only ballistic training induced adaptations in submaximal

measurements. High force contractions have long been utilized in rehabilitation and sports performance enhancement arenas to maximize strength development. However, high velocity (ballistic) training is not as common. For patients or clients requiring rapid force output, this study supports the use of high velocity (ballistic) contractions in the training regime. Our use of high force levels in both the ramp and ballistic training contractions may have limited our ability to demonstrate training specificity in the MVIC testing conditions due to the carryover effects of high force training to multiple velocities of testing. However, at submaximal testing levels (150 ms into ballistic contraction) the ballistic trained group achieved significantly greater force output and approached significance for VA ($p=0.0516$). High velocity training exhibits a carryover effect in that force production is not only improved in high velocity training contractions, but also at lower velocities training contractions. Low velocity training has not exhibited a carryover effect to high velocity test contractions. Therefore, the inability of the ramp contraction trained group to achieve significant training adaptations in the submaximal test condition is not a surprise. This is yet another indication that patients or clients who require rapid force production should incorporate high velocity training contractions.

Conclusions

1. High force, slow ramp and fast ballistic contraction velocity training of the quadriceps femoris lead to adaptations in central mechanisms (higher levels of VA), which allowed greater force production after training.
2. High force, high velocity ballistic training contractions induced central mechanism adaptations resulting in accelerated rates of VA and force production during the initial phase of ballistic MVIC efforts.

3. High force, high velocity ballistic training contractions showed test-training specificity suggesting the need for matching and test and training contraction velocities.

Table 4-1. Group demographics (mean ± s.e.).

	Control Group (n=6, 3M:3F)	Ramp Group (n=9, 3M:6F)	Ballistic Group (n=8, 5M:3F)
Age (yrs)	23.5 ± 1.22	24.11 ± 3.14	23.75 ± 1.16
Height (cm)	173.13 ± 4.37	174.14 ± 10.24	179.71 ± 12.04
Weight (kg)	66.90 ± 6.21	72.98 ± 9.49	75.98 ± 14.82
BMI (kg/m^2)	22.37 ± 2.48	24.09 ± 2.58	23.38 ± 2.08
Activity Level	7.64 ± 0.73	7.56 ± 1.04	7.06 ± 1.17

One-way ANOVA revealed no significant between group differences; age p=0.8637, height p=0.3961, weight p=0.3018, BMI p=0.4101, activity level p=0.504.

Table 4-2. Training parameters.

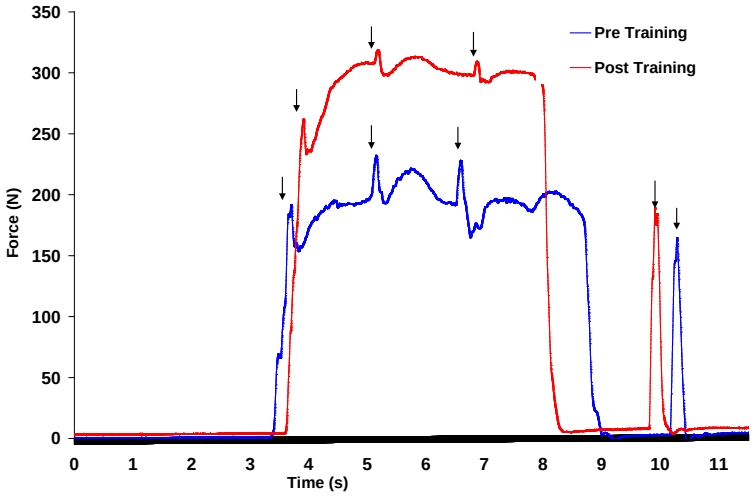
	Sets	Repetitions	Load	Rest Between Reps	Rest Between Sets
Week 1	3	6	100% MVIC	25 seconds	3 minutes
Week 2	3	8	100% MVIC	25 seconds	3 minutes
Weeks 3 - 6	3	10	100% MVIC	25 seconds	3 minutes

Table 4-3. Ramp test MVIC force and VA (means ± s.e.)

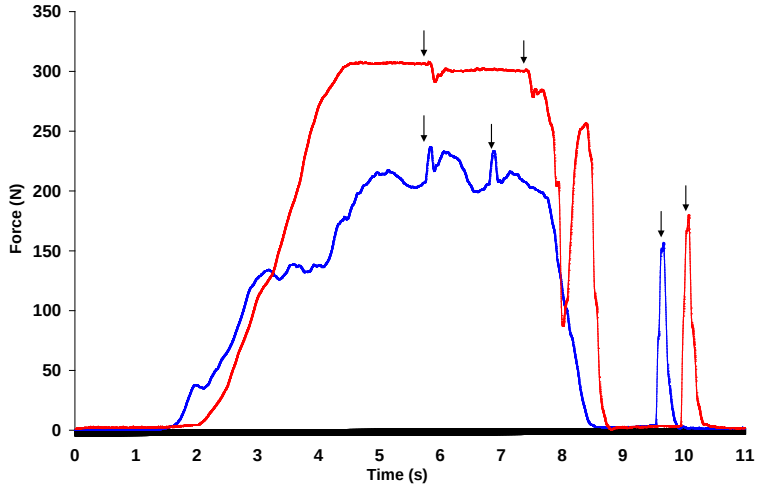
		Control Group	Ramp Group	Ballistic Group
MVIC Force (N)	Pre	704.59 (62.37)	694.52 (25.13)	856.44 (55.60)
	Post	704.95 (65.68)	833.41 (22.11)	990.47 (69.95)
	Post - Pre	0.36 (12.11)	138.89 (26.66)	134.02 (33.71)
MVIC VA (%)	Pre	86.18 (2.75)	90.51 (1.61)	92.82 (1.55)
	Post	81.83 (3.72)	97.51 (0.45)	96.62 (0.86)
	Post - Pre	-4.35 (1.72)	6.99 (1.62)	3.79 (1.57)

Table 4-4. Ballistic test MVIC force and VA (means ± s.e.)

		Control Group	Ramp Group	Ballistic Group
MVIC Force (N)	Pre	707.21 (63.16)	692.84 (31.13)	837.43 (58.77)
	Post	703.94 (64.37)	816.39 (20.39)	995.51 (67.34)
	Post - Pre	-3.28 (14.58)	123.55 (30.41)	158.07 (28.99)
MVIC VA (%)	Pre	86.96 (2.28)	89.04 (1.84)	89.57 (2.18)
	Post	79.95 94.12)	96.51(0.81)	96.60 (0.88)
	Post - Pre	-7.00 (2.03)	7.46 (1.72)	7.02 (2.06)
150 ms Force (N)	Pre	319.65 (40.61)	275.91 (31.42)	406.24 (36.99)
	Post	287.82 (34.44)	315.33 (40.01)	604.34 (67.00)
	Post - Pre	-31.82 (15.67)	39.42 (21.69)	198.11 (53.14)
150 ms VA (%)	Pre	42.63 (3.74)	36.24 (4.98)	45.00 (2.10)
	Post	36.09 (3.27)	39.80 (4.59)	59.20 (3.44)
	Post - Pre	-6.54 (2.39)	3.57 (3.12)	14.20 (4.03)



A



B

Figure 4-1. Experimental trace of pre and post-training ballistic tests from a ballistic training subject (figure A) and pre and post-training ramp tests from a ramp training subject (figure B).

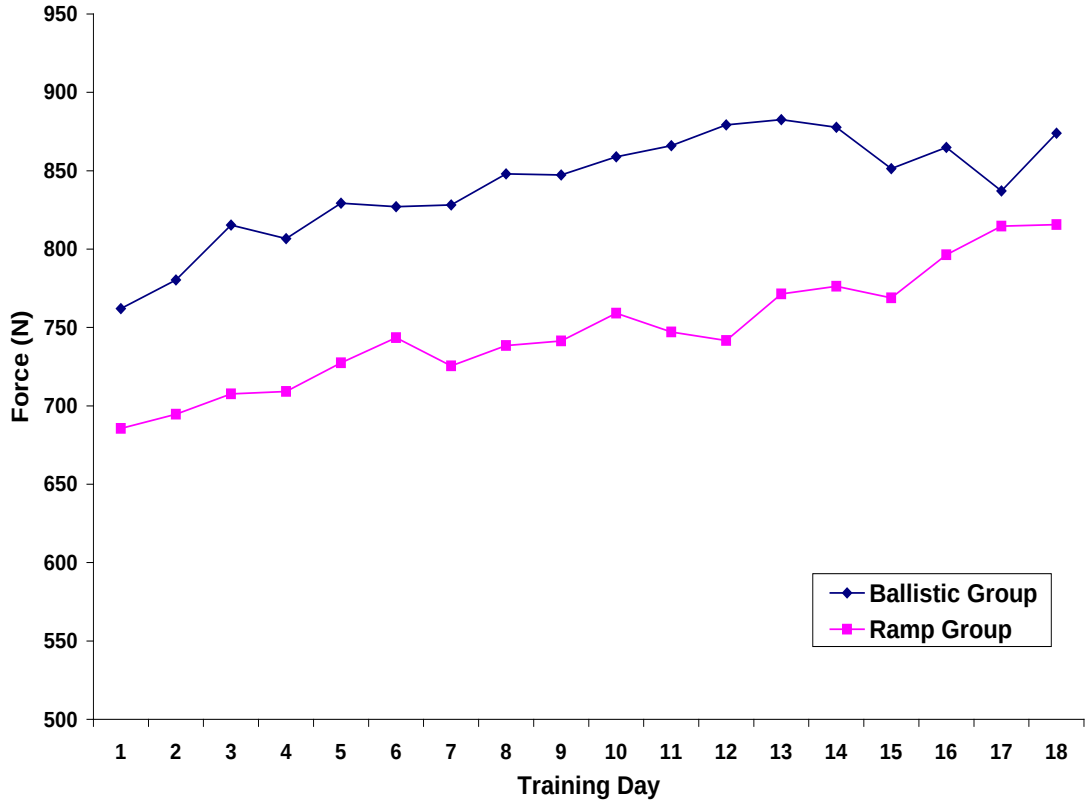


Figure 4-2. Daily graining log: group mean MVIC force.

Note: Throughout the training period the ramp group demonstrated a compliance level of 100% while the ballistic group had a compliance level of 95.1% (completed training sessions/total possible training sessions).

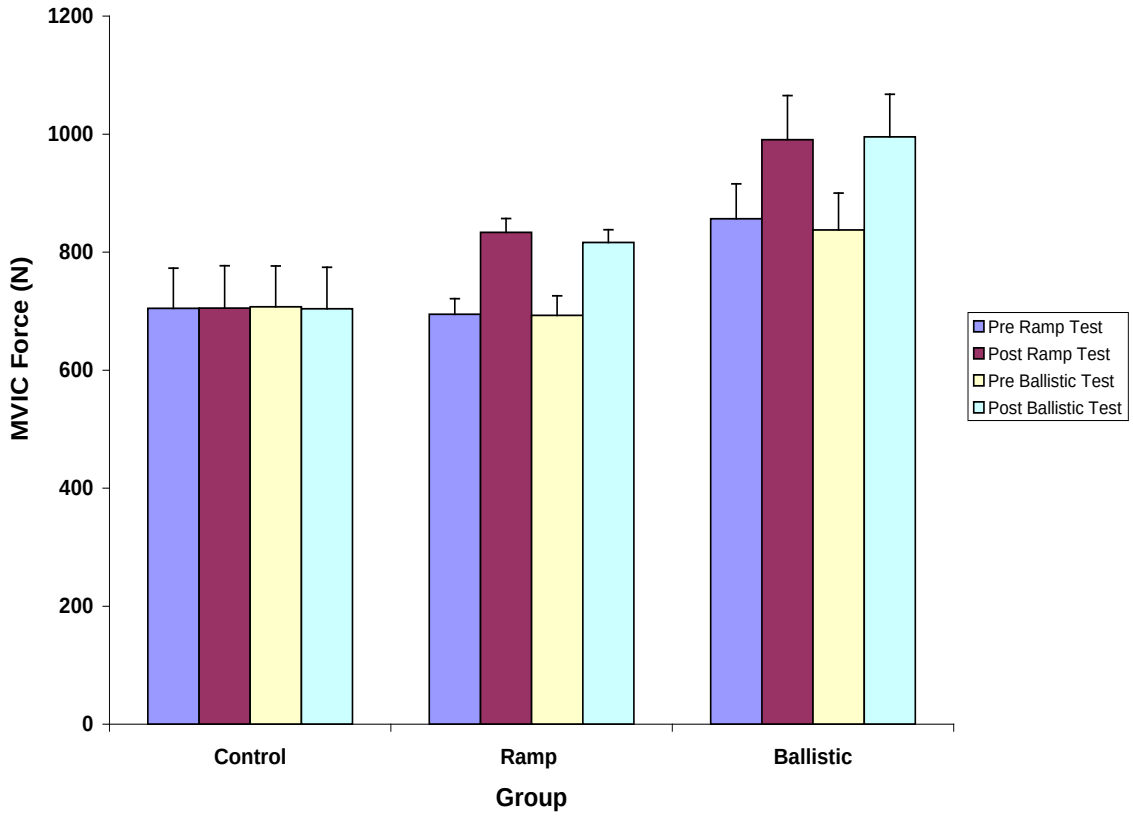


Figure 4-3. Pre and post training MVIC force levels (means ± s.e.)

Note: Pre-training analysis: Bonferroni adjusted t-tests (α level of 0.05/6 = 0.008): control vs. ramp group, ballistic test (t=0.2, p=0.8407), control vs. ballistic group, ballistic test (t=1.8, p=0.0868), ramp vs. ballistic group, ballistic test (t=2.22, p=0.0379), control vs. ramp group, ramp test (t=0.14, p=0.8881), control vs. ballistic group, ramp test (t=2.1, p=0.0486), and ramp vs. ballistic group, ramp test (t=2.49, p=0.0217).

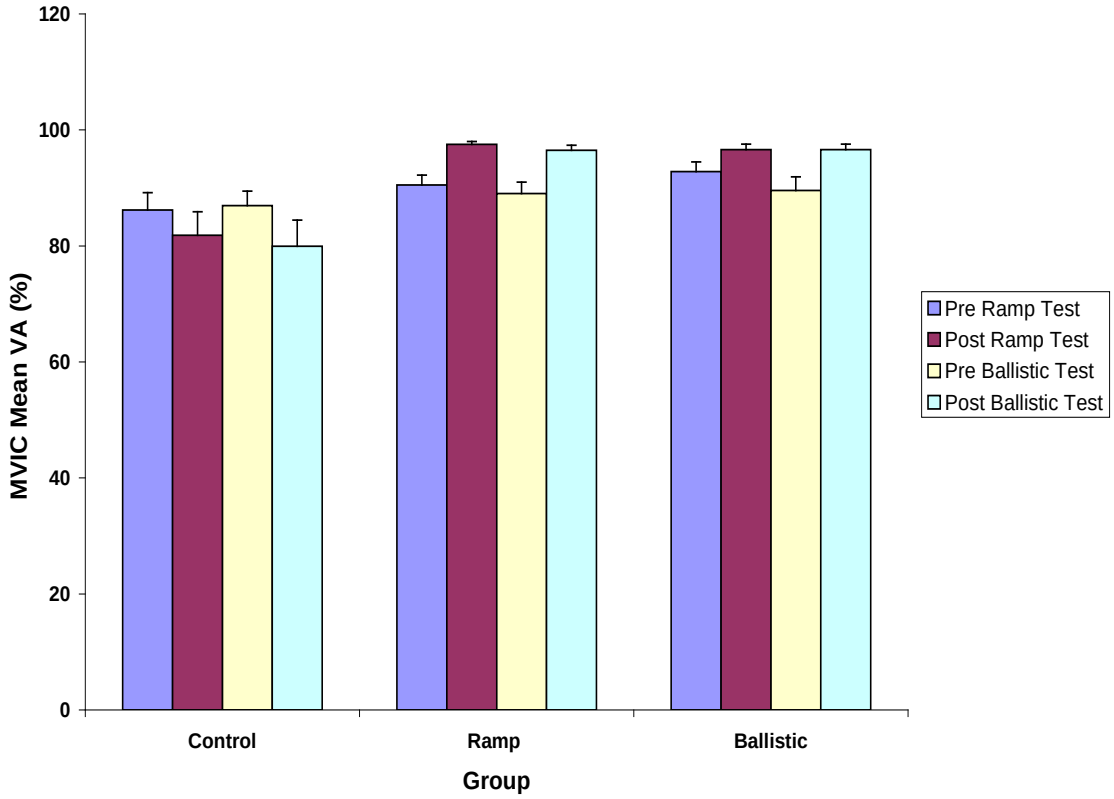


Figure 4-4. Pre and post-training MVIC VA levels (means ±.s.e.)

Note: Pre-training analysis: Bonferroni adjusted t-tests (α level of 0.05/6 = 0.008): control vs. ramp group, ballistic test (t=0.72, p=0.4786), control vs. ballistic group, ballistic test (t=0.88, p=0.3878), ramp vs. ballistic group, ballistic test (t=0.2, p=0.8455), control vs. ramp group, ramp test (t=1.49, p=0.1491), control vs. ballistic group, ramp test (t=2.23, p=0.0355), and ramp vs. ballistic group, ramp test (t=0.86, p=0.3977).

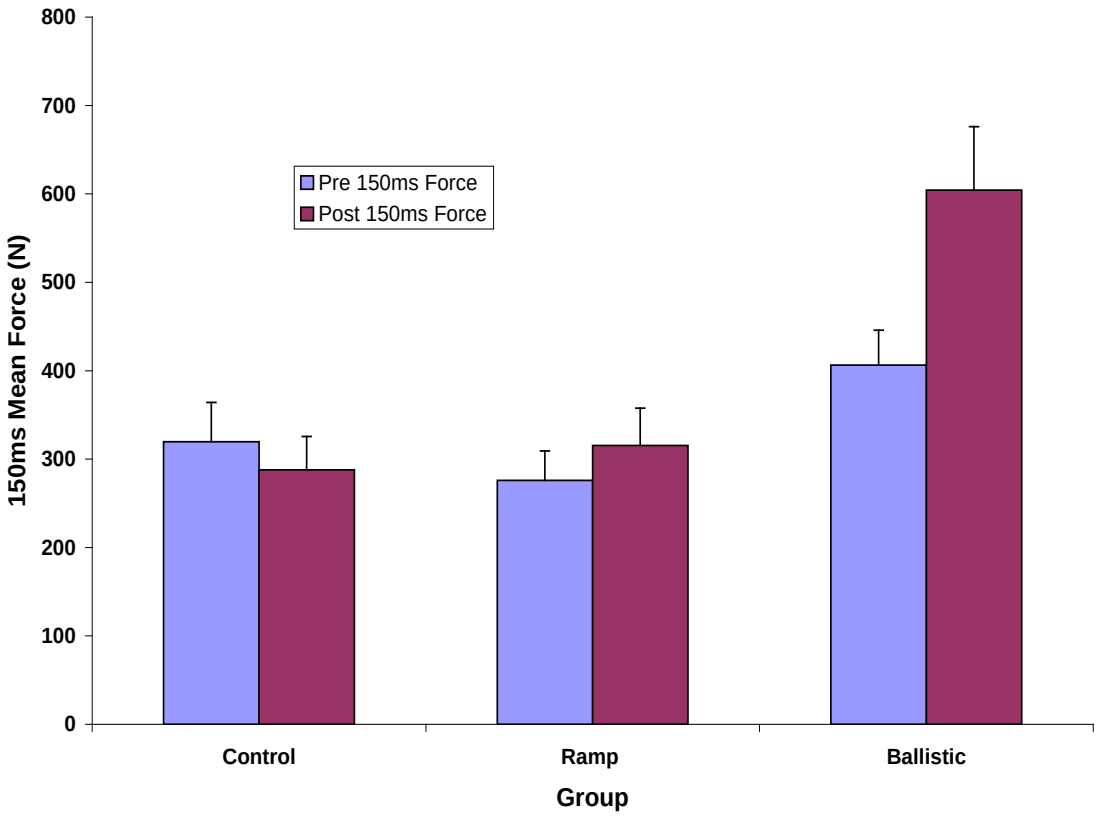


Figure 4-5. Pre and post-training of 150 ms ballistic test force levels (means ± s.e)

Note: Pre-training analysis: Bonferroni adjusted t-tests (α level of 0.05/3 = 0.0166): control vs. ramp group (p=1), control vs. ballistic group (p=0.1457), and ballistic vs. ramp group (p=0.0515).

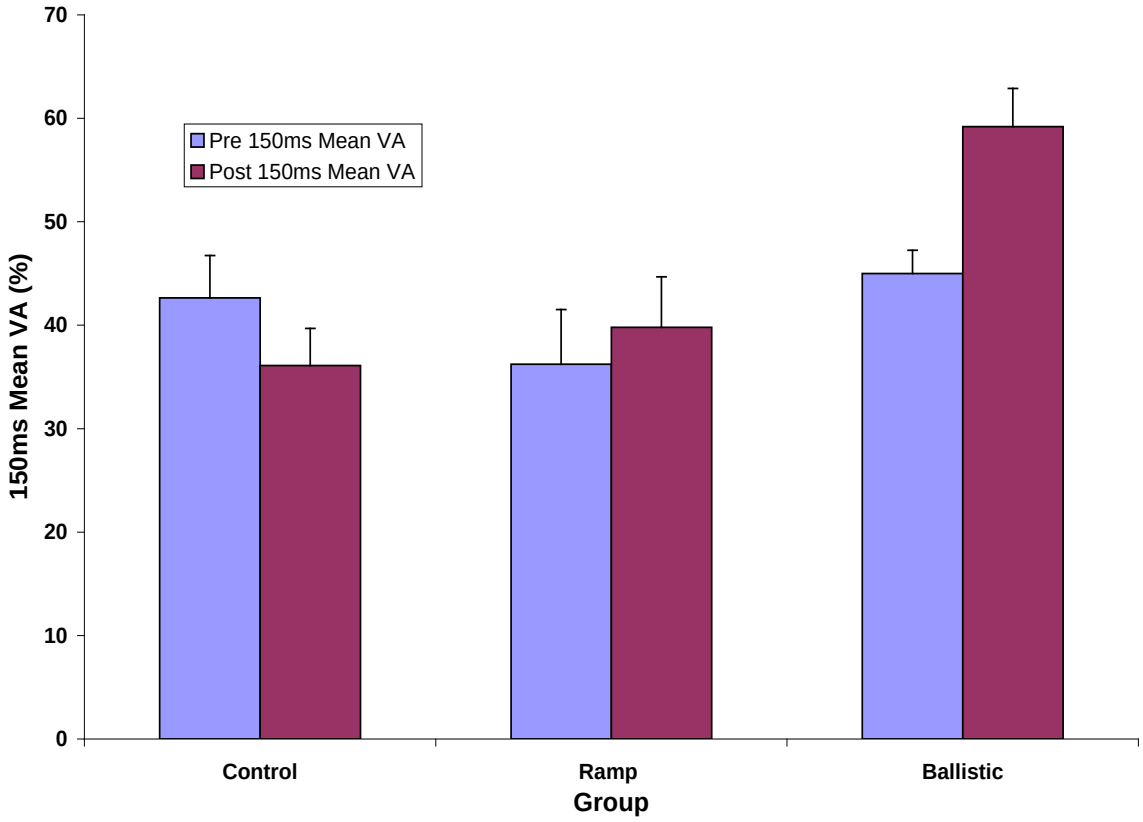


Figure 4-6. Pre and post-training of VA for 150 ms ballistic test (means ± s.e.)

Note: Pre-training analysis: Bonferroni adjusted t-tests (α level of 0.05/3 = 0.0166): control vs. ramp group (p=0.8578), control vs. ballistic group (p=1), and ballistic vs. ramp group (p=0.3569).

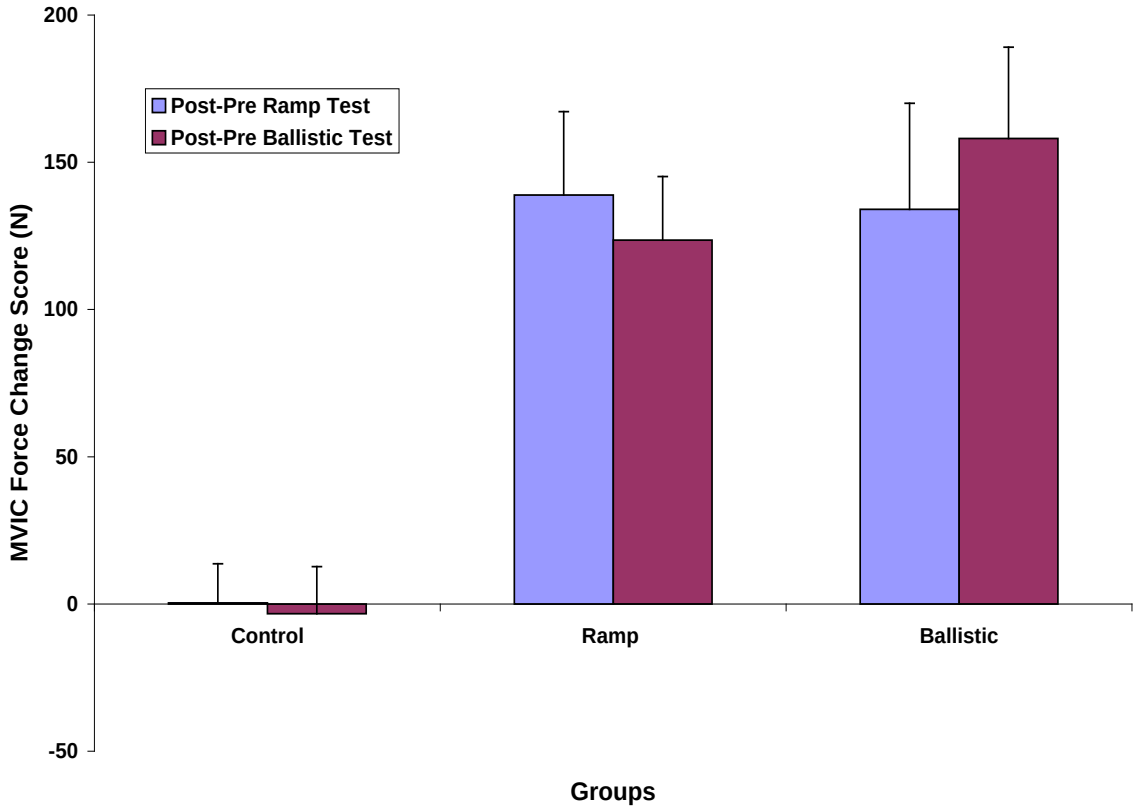


Figure 4-7. Post minus pre-training MVIC force change scores (means ±.s.e.)

Note: Placebo Effect: Control group post-pre ramp test (p=0.9772), post-pre ballistic test (p=0.8311).
General Training Effect: Ramp group post-pre training on ramp test (p=0.0008), on ballistic test (p=0.0036). Ballistic group post-pre training on ramp test (p=0.0053), on ballistic test (p=0.001).
Training efficacy: Bonferroni adjusted t-tests (α level of 0.05/4 = 0.0125): control vs. ramp group, ramp test (t= 3.28, p=0.0039), control vs. ballistic group, ramp test (t=3.44, p=0.0025), control vs. ramp group, ballistic test (t= 2.98, p=0.0076), and control vs. ballistic group, ballistic test (t= 4.04, p=0.0006).
Training Specificity: Bonferroni adjusted t-tests (α level of 0.05/3 = 0.017): ramp vs. ballistic group, ramp test (t= 0.69, p=0.4965), ramp vs. ballistic group, ballistic test (t=1.43, p=0.1706), and ramp group ramp test vs. ballistic group ballistic test (t=1.11, p=0.2817).
Test-Training Specificity: Paired t-tests (α level of 0.05): ramp group, ramp vs. ballistic test (t= 1.64, p=0.1217), ballistic group, ramp vs. ballistic test (t=2.42, p=0.0284).

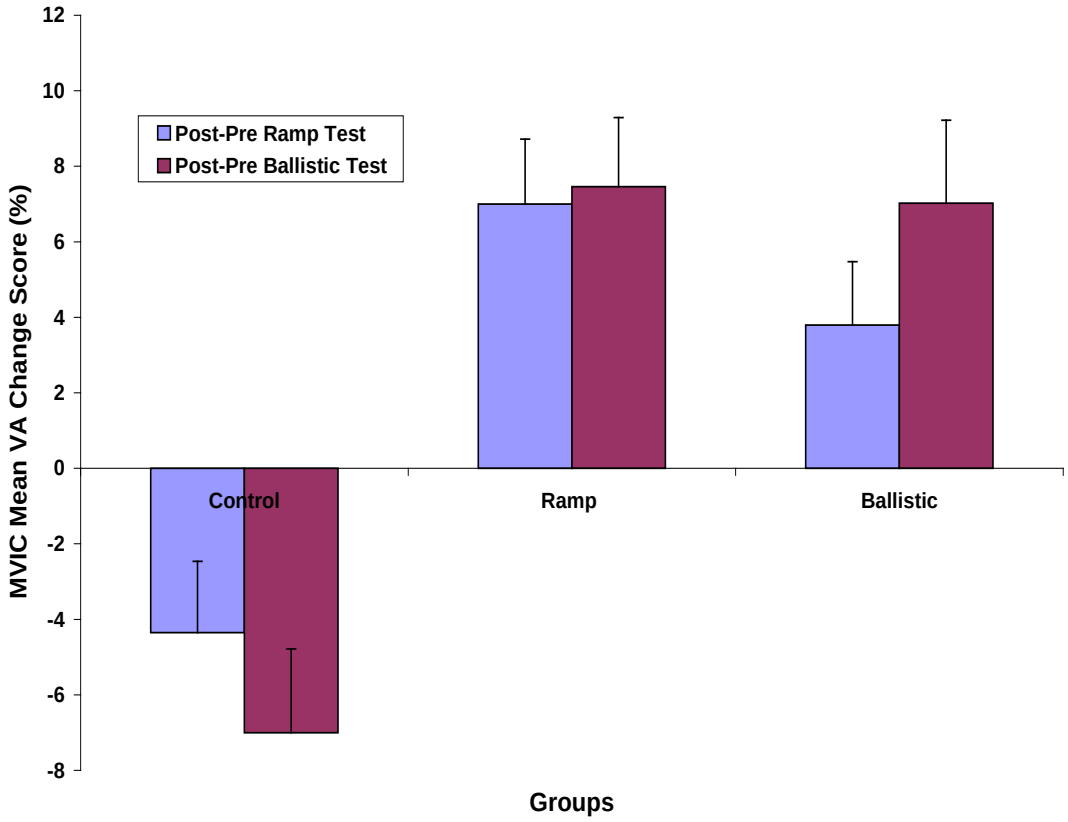


Figure 4-8. Post minus pre-training MVIC VA change scores (means ±.s.e.)

Note: Placebo Effect: Control group post-pre ramp test (p=0.0527), post-pre ballistic test (p=0.0182).
General Training Effect: Ramp group post-pre training on ramp test (p=0.0025), on ballistic test (p=0.0025). Ballistic group post-pre training on ramp test (p=0.0461), on ballistic test (p=0.0113).
Training efficacy: Bonferroni adjusted t-tests (α level of 0.05/4 = 0.0125): control vs. ramp group, ramp test (t= 4.33, p=0.0002), control vs. ballistic group, ramp test (t=3.03, p=0.0059), control vs. ramp group, ballistic test (t= 5.52, p < 0.0001), and control vs. ballistic group, ballistic test (t=5.22, p < 0.0001).
Training Specificity: Bonferroni adjusted t-tests (α level of 0.05/3 = 0.0166): ramp vs. ballistic group, ramp test (t= 1.29, p=0.2129), ramp vs. ballistic group, ballistic test (t= 0.18, p=0.8611), and ramp group ramp test vs. ballistic group ballistic test (t= 0.01, p=0.9929).
Test-Training Specificity: Paired t-tests (α level of 0.05): ramp group, ramp vs. ballistic test (t= 0.54, p=0.5956), ballistic group, ramp vs. ballistic test (t=3.57, p=0.0028).

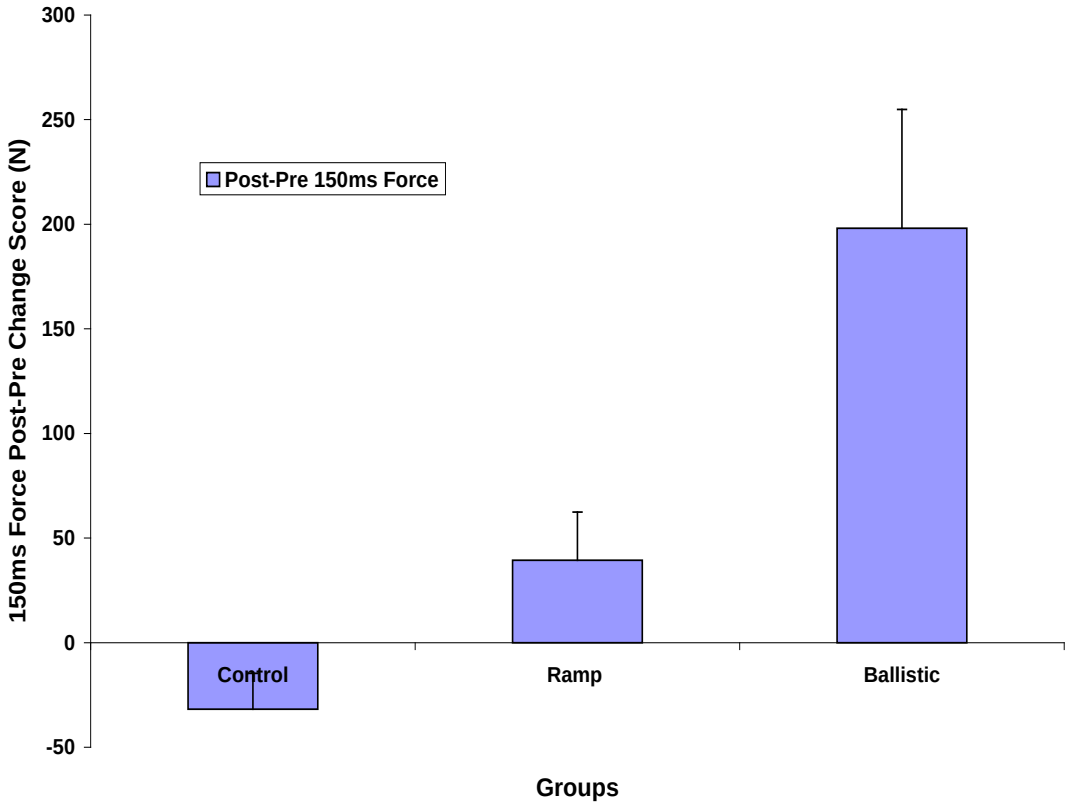


Figure 4-9. Post minus pre-training 150 ms ballistic force change scores (means ±.s.e.)

Note: Placebo Effect: Control group post-pre 150ms force (p=0.0979).
General Training Effect: Post-pre-training 150ms force ramp group (p=0.1067), ballistic group (p=0.0074).
Training efficacy: Bonferroni adjusted t-tests (α level of 0.05/2 = 0.025); ramp vs. control group (p=0.609) and between the ballistic and control group (p=0.004).
Training Specificity: Comparison of the two training groups at 150ms of the ballistic test revealed a significant between training group difference for 150ms force (f=8.33, p=0.0113).

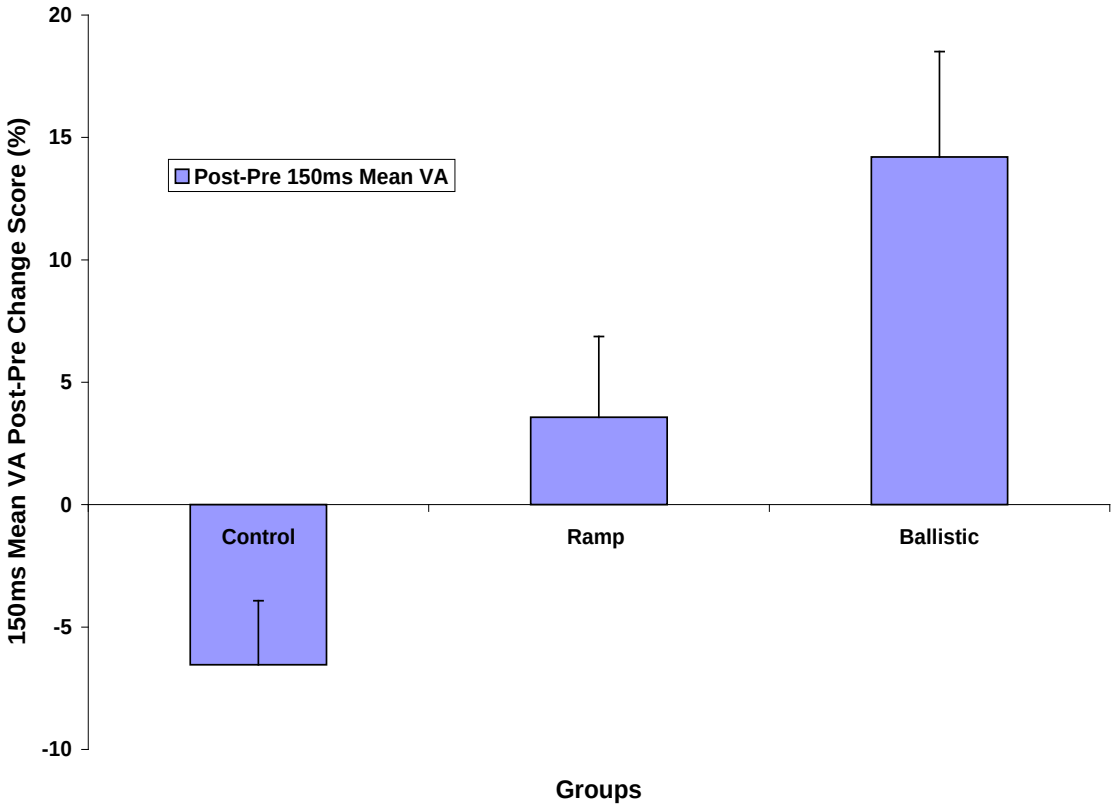


Figure 4-10. Post minus pre-training 150 ms ballistic VA change scores (means ±.s.e.)

Note: Placebo Effect: Control group post-pre 150ms VA (p=0.0411).
General Training Effect: Post-pre-training 150ms VA ramp group (p=0.2855), ballistic group (p=0.0096).
Training efficacy: Bonferroni adjusted t-tests (α level of 0.05/2 = 0.025); ramp vs. control group (p=0.1664) and between the ballistic and control group (p=0.0018).
Training Specificity: Comparison of the two training groups at 150ms of the ballistic test revealed a nearly significant between training group difference for 150 ms mean VA (f=4.47, p=0.0516).

CHAPTER 5

CONCLUSIONS

Summary

The production of muscle force is dependent on the interaction of both central and peripheral mechanisms. Plasticity in these mechanisms has been demonstrated by adaptations of force output secondary to the effects of injury, disease, fatigue, aging, and training. The investigation of underlying contributing factors is of fundamental interest in the development of intervention strategies to improve muscle force production. The interpolated twitch technique (ITT) has been extensively used to evaluate voluntary activation (VA), a central mechanism of muscle force production. Use of the ITT to assess central mechanisms is appropriate only if the technique demonstrates a certain degree of validity and it is used appropriately. In this context, the ITT could be utilized as a measure for the investigation of training intervention effects on central mechanisms of force production.

The global intent of our research was to confirm the validity of the ITT to voluntary torque relationship (first study) and then to utilize this technique in developing definitive criterion measures enhancing the study of selected training strategies on central fatigue (second study), and contraction velocity specificity (third study) VA and force production outcomes. Randomized, controlled, repeated measures designs were used in both training studies.

While each of the specific aims was addressed, not all of the hypotheses were supported by the results of the studies. The specific aims and hypotheses as originally stated, along with the findings from each study are presented individually.

Assessment Of Voluntary Activation By Stimulation Of
One Muscle Or Two Synergistic Muscles

Specific Aim 1: To assess in healthy young adults the contribution of non-stimulated synergists to the non-linearity of the interpolated twitch-voluntary torque relationship for elbow flexion contractions. (Chapter 2).

Hypothesis 1a: Simultaneous stimulation of the biceps brachii and brachioradialis at rest and during a voluntary contraction will elicit significantly greater torque than that elicited by stimulation of the biceps brachii only.

Partially Supported: Simultaneous stimulation of the biceps brachii (BB) and brachioradialis (BR) at rest produced a statistically significant 73% increase in torque as compared to stimulation of the BB alone ($p < 0.05$). In contrast simultaneous BB and BR stimulation during multiple levels of voluntary effort was not greater than that produced by stimulation of BB alone ($p > 0.05$). These findings partially support Hypothesis 1a.

Hypothesis 1b: Simultaneous stimulation of the biceps brachii and brachioradialis will improve the linearity of the interpolated twitch-voluntary torque relationship of the elbow flexors as compared to stimulation of the biceps brachii alone.

Partially Supported: Both linear and polynomial models were used to study the interpolated twitch to voluntary torque relationship. In both stimulation conditions (BB and BB plus BR), a polynomial

model provided a better fit to the data (higher r^2 value) compared to the linear model. When comparing the two stimulation conditions, r^2 improved with the simultaneous stimulation (mean r^2 increased from 0.83 to 0.88 for the linear model, and 0.95 to 0.97 for the polynomial model). Statistical analysis revealed a significant interaction effect between stimulation condition and model type ($p < 0.05$) indicating a greater increase in r^2 for the linear fit. However, the general increase in r^2 with simultaneous stimulation of BB and BR was relatively modest and the main effect of stimulation condition on the r^2 value was not statistically significant ($p = 0.20$). These findings partially support Hypothesis 1b.

Since multiple synergist stimulation was not found to significantly improve the interpolated twitch to voluntary torque relationship for elbow flexion contractions, follow-up pilot work was conducted (Appendix A). The results of this pilot work identified the quadriceps femoris as a valid ITT test muscle model. The pilot work also provided valuable information in helping refine testing procedures in addition to ensuring confidence in our ability to safely proceed with the repetitive nature training aspects in studies two and three.

Investigation Of The Effect Of High Volume Isometric Strength Training Of The Quadriceps Femoris On Levels Of Voluntary Activation And Maximum Force Production Prior To, During, And After A Long Duration Fatigue Test Protocol

Specific Aim 2: To investigate in healthy young adults the effects of high volume voluntary isometric strength training of the quadriceps femoris on the level of MVIC VA and force production prior to, during, and after a fatiguing protocol (Chapter 3).

Hypothesis 2a: Subjects who voluntarily isometrically strength train the quadriceps femoris will demonstrate post- minus pre-training increases in MVIC VA and force production in the pre-fatigue state as compared to a control group who will demonstrate no change.

Supported: Efficacy analysis of the pre-fatigue data revealed significant increases in post- minus pre-training change scores for both MVIC force and VA. Placebo analysis revealed non-significant differences in the MVIC force and VA change scores.

The above findings support both aspects of Hypothesis 2a. From an experimental design perspective, the results verified the effectiveness of high volume MVIC strength training on inducing central adaptations in the underlying mechanisms of MVIC VA and force outcome measures.

Hypothesis 2b: Subjects who voluntarily isometrically strength train the quadriceps femoris pre to post training will maintain higher levels of MVIC VA and force production during a fatigue task as compared to a control group who will show no change.

Partially Supported: Efficacy analysis of the fatigue test data for the training group compared to the control group showed significant increases in post- minus pre-training change scores for the MVIC force and VA initial response and the predicted MVIC force and VA at minute one values. These findings support Hypothesis 2b.

The analysis of the slope of the MVIC force and VA versus fatigue time regression line, as compared to the control group, showed significant decreases (became more negative) in the post- minus pre-training change scores. Control group versus training group predicted end point MVIC force and VA, total endurance force volume, and total endurance time post- minus pre-training change scores were not significantly different. These findings do not support Hypothesis 2b.

Control group placebo effect analysis revealed non-significant post- minus pre-training change scores for all fatigue test outcome variables. This finding supports Hypothesis 2b.

The above findings indicated that high volume MVIC strength training was effective in increasing resistance to early

fatigue, but also demonstrated increased overall fatigue rates resulting in non-significant changes in total endurance time and endurance volume.

It is interesting to note that the fatigue test protocol (long duration, 25% MVIC low intensity, 16 second sustained, 3 per minute intermittent muscle contractions) that we used in this study was effective in fatiguing both the control group and training group to approximately the same pre- and post-training MVIC VA and force levels. These results provide valuable information of the potential utility of this protocol for use in future studies.

Hypothesis 2c: Subjects who voluntarily isometrically strength train the quadriceps femoris will demonstrate post- minus pre-training higher levels and more rapid recovery of MVIC VA and force production as compared to a control group who will demonstrate no change.

Supported: Efficacy analysis of the post-fatigue test recovery data for the training group compared to the control group showed significant increases in both MVIC force and VA post- minus pre-training change scores for recovery periods from RC2 to RC20. The MVIC force and VA increases in change scores for the training group were higher than the control group but did not reach statistical significance. The placebo effect analysis for the control

group revealed no significant post-minus pre-training change scores for any of the recovery time periods for neither the MVIC force nor VA. These findings support both aspects of Hypothesis 2c.

Time analysis of adjacent recovery periods of post- minus pre-training change scores for the training group showed a progressive increase in rate of recovery over the 20-minute recovery period for both MVIC force and VA. However, the only significant adjacent recovery period was RC0 versus RC1 for both MVIC force and VA. These results overall support the first part of Hypothesis 2c.

The control group placebo effect time analysis of adjacent recovery periods of post- minus pre-training change scores revealed no significant differences ($p \geq 0.0911$) for MVIC force. The placebo effect analysis for MVIC VA showed a significant difference for RC0 to RC1 but non-significant differences for all other adjacent recovery periods. These results overall support the second aspect of Hypothesis 2c.

The above findings substantiated the effectiveness of high volume MVIC strength training on enhancing central mechanisms of MVIC force and VA recovery from prolonged fatigue challenges. The results demonstrated both increased levels and rates of recovery in both MVIC force and VA. The predominance

of the recovery changes occurred within the first minute of recovery.

The Effect Of Ramped And Ballistic Isometric Strength Training Of The Quadriceps Femoris On Voluntary Activation And Force Production

Specific Aim 3: To examine in healthy young adults the effects of ramp (slow contraction velocity) and ballistic (fast contraction velocity) isometric contraction strength training on the level of VA and force production of the quadriceps femoris during MVIC ramp and MVIC ballistic testing and MVIC ballistic initial onset (150 ms) testing (Chapter 4).

Hypothesis 3a: In ramp and ballistic MVIC, and MVIC ballistic testing both ramp(slow contraction velocity) and ballistic (fast contraction velocity) training groups will demonstrate greater post- minus pre-training changes in MVIC VA and force production as compared to a control group who will show no change.

Supported: The efficacy analysis showed significant increases in post- minus pre-training change scores for the ramp and ballistic training groups compared to the control group on both the ramp and ballistic test conditions for MVIC force and VA. Post- minus pre-training change scores for force and VA on the submaximal 150 ms ballistic test for the ballistic training were significantly higher than for the control group. The ramp group versus control

group 150 ms ballistic test force and VA differences were not significant. In evaluating these last ramp group versus control group comparisons it is important to note that the post- minus pre-training change scores for the control group were negative while for the ramp group they were positive.

The placebo analysis revealed non-significant post- minus pre-training change scores for ramp and ballistic test MVIC force and ramp test MVIC VA. The ballistic test MVIC VA change score was significant; however, the change was negative. Control group post- minus pre-training change scores on the submaximal 150 ms ballistic test force measure was not significant but it was significant for VA, which was also a negative change.

The above findings support both aspects of Hypothesis 3a. From an experimental design perspective these results verified the effectiveness of the chosen interventions utilized for this study of high resistance ramp and ballistic MVIC strength training on inducing central mechanism adaptations in ramp and ballistic tested VA and force outcome measures.

Hypothesis 3b: The ballistic contraction trained group will demonstrate the greatest post- minus pre-training changes in VA and force production as compared to the ramp contraction trained group for MVIC ballistic and ramp testing and submaximal ballistic testing.

Minimally Supported: Training specificity analysis showed non-significant between training group differences in post- minus pre-training change scores for MVIC force on the ramp test, on the ballistic test, and on ramp versus ballistic test comparisons. Similar results were found for MVIC VA. Comparison of post-minus pre-training change scores on the submaximal 150 ms ballistic test showed higher training changes in VA and force for the ballistic trained group compared to the ramp trained group. The between training groups difference for VA approached statistical significance ($p= 0.0516$) and achieved significance for force ($p=0.0113$). This later comparison is the only result that supports Hypothesis 3b.

Collectively out of all eight of the VA and force post-minus pre-training changes scores between group comparisons only one contrast was found to be significant. These findings in general refute the tenet of enhanced training effects for ballistic contraction type MVIC strength training outcomes. In this context the findings only minimally support Hypothesis 3b.

Hypothesis 3c: Test-training specificity will be indicated by greater post- minus pre-training changes in VA and force during MVIC ramp testing compared to ballistic testing for the ramp contraction training group; and conversely higher VA and force production training

changes during MVIC ballistic testing compared to ramp testing for the ballistic contraction trained group.

Partially Supported: Test-training analysis of post- minus pre-training MVIC force and VA change scores for the ramp test versus the ballistic test for the slow ramp contraction trained group were not significant. In contrast the fast ballistic trained group showed significant test specific increases in the ballistic test MVIC force and VA. Based on the findings that test-training specificity was significant on only one test-training condition, the results only partially support Hypothesis 3c.

It is interesting to note that the fast contraction velocity ballistic trained group showed significant outcome results for both training specificity and test-training specificity analyses. These results provide partial support for potential training advantages of high velocity training strategies.

Conclusions

Assessment Of Voluntary Activation By Stimulation Of One Muscle Or Two Synergistic Muscles

1. Simultaneous stimulation of the biceps brachii and brachioradialis at rest produced significantly greater torque output than stimulation of the biceps brachii only.
2. Simultaneous stimulation of the biceps brachii and brachioradialis during multiple levels of voluntary effort did not significantly enhance torque output.

3. Simultaneous stimulation of the biceps brachii and the brachioradialis improved the linearity of the interpolated twitch to voluntary torque relationship but the increase in r^2 was moderate and not statistically significant.

Investigation Of The Effect Of High Volume Isometric Strength Training Of The Quadriceps Femoris On Levels Of Voluntary Activation And Maximum Force Production Prior To, During, And After A Long Duration Fatigue Test Protocol

1. In the non-fatigued state high force, high volume isometric strength training of the quadriceps femoris leads to adaptations in central mechanisms of MVIC VA and muscle force production allowing greater VA and force production after training.
2. High force, high volume isometric strength training of the quadriceps femoris leads to an increased resistance to the initial phase of fatigue but also increased rate of fatigue resulting in insignificant changes in total force volume and endurance time. This is possibly secondary to training induced adaptations which minimize the initial fatigue effects on MVIC force and VA and the overall increased level of MVIC force and VA output displayed through the first two-thirds of the fatigue task.
3. High force, high volume isometric strength training of the quadriceps femoris increased MVIC VA and force output at all recovery time periods. The predominance of the MVIC VA and force recovery adaptations occurred in the first minute of recovery.

The Effect Of Ramped And Ballistic Isometric Strength Training Of The Quadriceps Femoris On Voluntary Activation And Force Production

1. High slow force ramp and fast ballistic contraction velocity training of the quadriceps femoris lead to adaptations in central mechanisms (higher levels of VA), which allowed greater force production after training.
2. High force high velocity ballistic training contractions induced central mechanism adaptations resulting in accelerated rates of VA and force production during the initial phase of ballistic MVIC efforts.
3. High force high velocity ballistic training contractions showed test-training specificity suggesting the need for matching and test and training contraction velocities.

Implications

Various strength training strategies are commonly used by clinicians and scientists who treat and study people with different musculoskeletal disorders. Muscle force production is dependent on interactions of both central and peripheral mechanisms. Plasticity of these mechanisms has been demonstrated by adaptations of force output secondary to the effects of injury, disease, fatigue, aging, and training. Investigation of underlying contributing factors is an integral question to the development of improved intervention strategies. The ITT has been extensively used as a tool to evaluate VA as an index of central mechanisms of muscle force production. Our first study examined the interpolated twitch to voluntary torque relationship in a muscle model with multiple synergists. Findings of this study along with our pilot work pointed us toward using the technique in the quadriceps femoris muscle model, in which it is the sole prime mover for

knee extension. The findings of our two training studies substantiated the utility of the quadriceps femoris interpolated twitch to voluntary torque relationship. MVIC VA and force production showed near parallel pre- to post-training changes and test condition responses in both training studies. As an example in the fatigue study, pre- to post-training percentage increases in pre-fatigue MVIC VA and force were ~18% and ~23%, respectively. The percentage pre- to post-training changes for fatigue test minute one were MVIC VA ~43% and force ~34%. The percentage pre- to post-training changes for fatigue test recovery at minute one were MVIC VA ~23% and force ~20%. These results support the premise of the interdependence between central mechanisms and force output. The results also show the plasticity of these systems in responding to the acute stress effects of fatigue and prolonged general overload stress of high volume, high resistance exercise training.

In the second training study, where ramp and ballistic training contractions were utilized, insight was gained regarding training velocity specificity on central mechanisms of VA and force production. High force ballistic training contractions appear to have a preferential effect on central mechanism adaptations resulting in accelerated rates of VA and force production during the initial phase (150 ms onset time) of ballistic MVIC efforts. Again VA and force measures showed parallel test responses and training changes. Of practical importance the ballistic contraction training specificity observed in this study has implication for the consideration of matching test and training velocities for future studies.

APPENDIX A

PILOT WORK: INVESTIGATION OF THE LINEARITY OF THE INTERPOLATED TRAIN TO ONGOING FORCE RELATIONSHIP OF THE QUADRICEPS FEMORIS

Relationship of the Interpolated Train to Ongoing Force in the Quadriceps Femoris

Several studies have demonstrated the interpolated torque (extra torque) to voluntary torque relationship to be non-linear at high force levels, and it has been suggested that this non-linear relationship is due to the contribution of non-stimulated synergists (Belanger and McComas 1981; Rutherford, Jones et al. 1986; Dowling, Konert et al. 1994). However, we were unable to demonstrate that by stimulating multiple synergists the interpolated twitch (extra torque) to voluntary torque relationship would be significantly improved (Williams and Bilodeau 2004). Therefore, an alternative muscle group was sought to fulfill three requirements: 1) it is the only prime mover/synergist of the joint it crosses, 2) it has a normally low level of voluntary activation in healthy subjects as compared to other muscle groups, and 3) it has a linear relationship between the interpolated torque (extra torque) and voluntary torque.

The quadricep is the prime mover/singular synergist for knee extension and is a very important muscle for functional independence in ADLs, work, and recreational activities. Behm and colleagues, 2002 investigated differences in voluntary activation in the ankle plantar and dorsiflexors, elbow flexors, and quadriceps and found average inactivation values of 5.0, 5.0, 1.3, and 15.5%, respectively (Behm, Whittle et al. 2002). Their findings are in line with values of activation reported by other investigators for the same muscle groups - quadriceps (Behm and St-Pierre 1997; Hurley, Rees et al. 1998; Roos, Rice et al. 1999; Stackhouse, Dean et al. 2000; Becker and Awiszus 2001;

Stackhouse, Stevens et al. 2001), biceps brachii (Allen, McKenzie et al. 1998; De Serres and Enoka 1998; Williams, Sharma et al. 2002; Williams and Bilodeau 2004), ankle plantar flexors (Loscher, Cresswell et al. 1996; Scaglioni, Ferri et al. 2002; Shima, Ishida et al. 2002), and tibialis anterior (Gandevia and McKenzie 1988; Connelly, Rice et al. 1999). Secondary to demonstrating this normally low level of voluntary activation, the quadricep represents a muscle in which a training effect could more easily be shown. Furthermore, a linear relationship between the interpolated torque (extra torque) and voluntary torque has been demonstrated for the quadriceps muscle (Chapman SJ 1985; Rice, Vollmer et al. 1992), therefore satisfying the third requirement.

Prior to initiating studies examining the level of voluntary activation of the quadriceps, pilot studies were performed to determine: 1) that the electrical stimulator (Digitimer Model DS7A) could elicit a meaningful amount of force from the quadriceps femoris with either a doublet or train of stimuli (doublet and train stimuli were assessed because we wanted to be able to perform fatigue studies and due to the slowing of contractile properties with fatigue [low frequency fatigue] high frequency stimulation is needed), 2) if we could replicate the linear interpolated torque (extra torque) to voluntary torque relationship that had been demonstrated by other authors, and 3) which angle of knee flexion was optimal for testing and potential training the quadriceps femoris.

Doublet and train stimulation were compared in two pilot subjects for force elicited at rest and it was found that train stimulation resulted in ~65% greater force being elicited at rest. Supramaximal train stimulation was then applied at rest in 3 pilot subjects to determine elicited force levels and subject tolerance. Utilizing this train stimulation, force elicited at rest was 72% of the maximal voluntary force. All subjects tolerated this stimulation well when applied at rest and during contractions. This level of elicited control force greatly exceeds the 25% of maximal voluntary contraction force that has been demonstrated to have a linear relationship with the voluntary torque at which the twitches were elicited (Bulow, Norregaard et al. 1995; Awiszus, Wahl et al.

1997). By eliciting such large control twitches we will enhance our ability to detect small activation deficits due to the fact that for a given level of system resolution, smaller activation deficits can be detected when the control twitches are larger (Shield and Zhou 2004). The resolution of our force measurement system is 0.75 N. This is less than 1% of the control twitch which averaged 631.4 N across three pilot subjects. By maximizing elicited control twitches and combining that with high measurement system resolution we will be able to measure very small changes in VA.

To determine if we could replicate the linear interpolated torque (extra torque) to voluntary torque relationship that has been demonstrated by other authors, three pilot subjects completed isometric quadriceps contractions to 10, 20, 30, 40, 50, 60, 70, 80, 85, 90, and 95%, and MVIC with sensitive ITT applied. The ongoing to evoked force and ongoing force to VA relationships are displayed in Figure A-1, with a linear model fit to each subject's data. The relationships are shown to be highly linear throughout the full range of voluntary forces, thus replicating the demonstrated relationship and demonstrating our ability to measure small changes in evoked force and the subsequent changes in VA.

To establish the optimal angle for testing and training of the quadriceps femoris a number of factors were considered. The majority of studies which have examined voluntary activation of the quadriceps femoris have done so at 90° of knee flexion (Bulow, Norregaard et al. 1993; Hurley and Newham 1993; Urbach, Nebelung et al. 1999; Stackhouse, Dean et al. 2000; Stackhouse, Stevens et al. 2001; Berth, Urbach et al. 2002; Urbach and Awiszus 2002; Stackhouse, Stevens et al. 2003; Becker, Berth et al. 2004; Chmielewski, Stackhouse et al. 2004; Lewek, Rudolph et al. 2004). Not only would utilizing this angle facilitate comparison across studies, but it could also enhance our ability to elicit quadriceps fatigue secondary to the fact that quadriceps endurance decreases with increasing muscle length (Ng, Agre et al. 1994; Hisaeda, Shinohara et al. 2001). This angle of knee flexion was used in pilot work in which three subjects

completed isometric testing and training of their quadriceps at 90° of knee flexion. Two subjects completed the testing and training protocol successfully, but one subject developed distal quadriceps femoris muscle irritation at the end of the training period. By decreasing the angle of knee flexion from 90° to 45° the external torque placed on the quadriceps is decreased to approximately 70% of maximum, and the patellofemoral compression force, secondary to the resultant force vector created by the pull of the quadriceps femoris muscle group and the patellar tendon, is reduced (Neumann 2002). This angle of knee flexion also represents a more functional angle around which the dynamic stabilizers of the knee function in ADLs, work, and sporting activities, and it has been suggested that studies investigating voluntary activation of the knee extensors should be conducted at more extended knee joint angles due to their greater similarity to the knee joint angles used in daily activities (Becker and Awiszus 2001) . Three pilot subjects then completed an identical training and testing protocol with the knee at 45° of knee flexion, and none of these subjects developed any quadriceps muscle or patellofemoral irritation.

This pilot work allowed us to demonstrate that we could elicit significant control torques in a manner that subjects tolerated well and, coupled with the sensitive force measurement system we are utilizing, would allow us to accurately measure small increments of superimposed torque. Using this force measurement system and these stimulation parameters we were able to replicate the strong linear relationship between interpolated torque (extra torque) and voluntary torque that has been demonstrated by others. Furthermore, this pilot work has demonstrated that although the majority of studies have utilized 90° of knee flexion as their testing/training angle it may not represent an ideal knee flexion angle for our studies which include multiple training contractions and/or multiple contractions in a fatigue protocol. Having completed this preliminary work I move forward with confidence that I am using a valid technique and

will be able to safely and successfully measure adaptations in central mechanisms of muscle force production that occur as a result of voluntary resistance training.

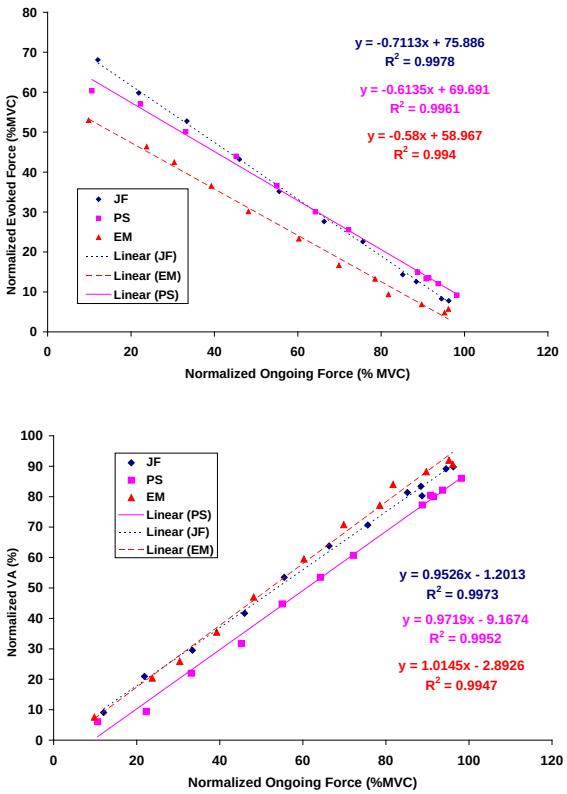


Figure A-1 Ongoing to evoked force relationship (top panel) and ongoing force to VA relationship (bottom panel) with linear models fit to and displayed for individual subject's data. The relationships are linear throughout the force spectrum.

APPENDIX B

BAECKE QUESTIONNAIRE OF HABITUAL PHYSICAL ACTIVITY

Baecke JA, Buerma J, and Frijters JE. A short questionnaire for the measurement of habitual physical activity in epidemiological studies. *American Journal of Clinical Nutrition* 36:936-942, 1982 Baecke J.

Work Activity

1.	What is your main occupation 1. "Low Level" eg. Office or clerical work, driving, shop keeping, teaching, or studying 2. "Middle Level" eg. Factory work, plumbing or carpentry 3. "High Level" eg. Dock work or construction work	1 – 3 – 5
2.	At work I sit Never/seldom/sometimes/often/always	1-2-3-4-5
3.	At work I stand Never/seldom/sometimes/often/always	1-2-3-4-5
4.	At work I walk Never/seldom/sometimes/often/always	1-2-3-4-5
5.	At work I lift heavy loads Never/seldom/sometimes/often/very often	1-2-3-4-5
6.	After working I am tired Never/seldom/sometimes/often/always	5-4-3-2-1
7.	At work I sweat Very often/often/sometimes/seldom/never	5-4-3-2-1
8.	In comparison with others my own age I think my work is physical Very often/often/sometimes/seldom/never	5-4-3-2-1

Work Activity Score = [((1) +((2) –6) + (3) + (4) + (5) + (6) + (7) + (8))/8]

Sports Activity

9.	Do you play sports If yes: Which sports do you play most frequently	Yes/No Intensity 0.76 – 1.26 – 1.76
	How many hours a week?	Time 0.5 – 1.5 – 2.5 – 3.5 – 4.5
	How many months a year?	Proportion 0.04 – 0.17 – 0.42 – 0.67 - 0.92

S1 = intensity x time x proportion + _____

If you play a second sport:

Intensity
0.76 – 1.26 – 1.76

Which sports do you play most frequently

Time 0.5 – 1.5 – 2.5 – 3.5 – 4.5

How many hours a week?

Proportion 0.04 – 0.17 – 0.42 – 0.67

How many months a year?

- 0.92

S2 = intensity x time x proportion = _____; S1 + S2 = _____

0 (no sport reported) = 1; 0.01 - <4 = 2; 4 - <8 = 3; 8 - <12 = 4; >12 = 5

10. In comparison with others my own age I think my physical activity during leisure time is
Much more/more/the same/less/much less — 5-4-3-2-1

11. During leisure time I sweat
Very often/often/sometimes/seldom/never — 5-4-3-2-1

12. During leisure time I play sports
Never/seldom/sometimes/often/very often — 5-4-3-2-1

Sports Activity Score = [((9) + (10) + (11) + 12))/4]

Non-Sports Leisure Activity

13. During leisure time I watch television
Never/seldom/sometimes/often/very often — 1-2-3-4-5

14. During leisure time I walk
Never/seldom/sometimes/often/very often — 1-2-3-4-5

15. During leisure time I cycle
Never/seldom/sometimes/often/very often — 1-2-3-4-5

16. How many minutes do you walk and/or cycle per day to and from work, school, and shopping?
<5 5-15 15-30 30-45 >45 — 1-2-3-4-5

Non Sports Leisure Activity Score = [((6-(13)) + (14) + (15) + (16))/4]

Total Score = (Work Activity) + (Sports Activity) – (Non Sports Leisure Activity)

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