

THE EFFECTS OF ACUTE MUSCULAR FATIGUE ON THE FUNCTIONAL
ABILITY OF THE KNEE JOINT

by

Tyler Nolan Brown

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Health and Human Development

MONTANA STATE UNIVERSITY
Bozeman, MT

November 2005

© COPYRIGHT

by

Tyler Nolan Brown

2005

All Rights Reserved

APPROVAL

of a thesis submitted by

Tyler Nolan Brown

The thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

Michael E. Hahn, Ph.D.

Approved for the Department of Health and Human Development

Craig Stewart, Ed.D.

Approved for the College of Graduate Studies

Joseph Fedock, Ph.D.

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Tyler Nolan Brown

November 2005

TABLE OF CONTENTS

1. INTRODUCTION.....	1
Development of Problem.....	1
Background.....	2
Statement of Purpose.....	4
Aims of the Study.....	4
Primary Hypothesis.....	4
Secondary Hypothesis.....	5
Tertiary Hypothesis.....	5
Assumptions.....	5
Limitations.....	6
Operational Definitions.....	6
2. LITERATURE REVIEW.....	8
Introduction.....	8
Fatigue.....	9
Electromyography.....	13
Force.....	14
The EMG/Force Relationship.....	15
The Effects of Fatigue on the EMG/Force Relationship.....	18
Functional Tests.....	19
3. METHODOLOGY.....	22
Subjects.....	22
Procedures.....	22
Pre-fatigue Functional Ability Tests.....	23
Fatigue Protocol.....	26
Post-fatigue Functional Test.....	27
Instrumentation.....	29
Strain-gauge Dynamometer.....	29
EMG Recording System.....	29
Post-Processing.....	29
Analysis.....	32
4. RESULTS.....	33
Subject Characteristics.....	33
Peak Isometric Torque.....	33
Distinguishing Phases of the Fatigue Protocol.....	34

TABLE OF CONTENTS- CONTINUED

Isokinetic Torque Production.....	34
EMG/Torque Ratio.....	36
Functional Tests.....	42
5. DISCUSSION.....	48
Introduction.....	48
Subject Characteristics.....	49
Torque Production.....	50
EMG/Torque Ratio.....	52
Functional Tests.....	55
6. CONCLUSION.....	58
REFERENCES CITED.....	61
APPENDICES.....	68
APPENDIX A: SUBJECT CONSENT FORM.....	69
APPENDIX B: SUBJECT ACTIVITY QUESTIONNAIRE.....	74

LIST OF TABLES

Table		Page
3.1	Demographic and anthropometric data of the sample: Mean (SD).....	23
4.1	Peak isometric knee extensor torque normalized to body mass for both samples: Mean (SD).....	34
4.2	2-Factor ANOVA with repeated measures of the fatigue protocol phases.....	37
4.3	Mean and standard deviations of EMG/Torque ratio during each phase.....	38
4.4	2-Factor ANOVA with repeated measures for the EMG/Torque ratio during each phase for the two types of responders to acute muscular fatigue.....	39
4.5	2-Factor ANOVA with repeated measures of phase for the EMG/Torque ratio of only the males subjects for the strength and endurance-trained samples.....	41
4.6	Pre-fatigue and post-fatigue parameters for the single-leg hop tests: Mean (SD).....	43

LIST OF FIGURES

Figure	Page
3.1 A diagram of the 3-Forward consecutive hop functional ability test.....	24
3.2 A diagram of the Figure-8 hop functional ability test.....	24
3.3 A diagram of the Up/Down hop functional ability test.....	25
3.4 A diagram of the M/L hop functional ability test.....	25
3.5 Setup of leg to lever arm and force transducer of the KIN-COM dynamometer.....	28
3.6 An example of a subjects torque production during each phase of the fatigue protocol.....	30
4.1 Peak concentric torque production during the fatigue protocol, broken into three phases. The first dashed line represents the Initial phase. The solid black line represents the Decline phase and the second dashed line represents the Fatigue phase.....	35
4.2 Torque production for each subject during each of the three phases (n = 22). Grey lines represent the strength-trained group and the black line represents the endurance-trained group.....	36
4.3 Mean torque production for both the strength-trained (n = 11) and endurance-trained (n = 11) samples during each of three phases. (* significane at alpha < 0.05).....	37
4.4 Average EMG/Torque ratio for both the strength-trained (n = 10) and endurance-trained (n = 9) samples for each of the three phases.....	38
4.5a Average EMG/Torque ratios for the ‘incliners’ (n = 9) during the three phases of the fatigue protocol.....	40
4.5b Average EMG/Torque ratios for the ‘decliners’ (n = 10) during the three phases of the fatigue protocol.....	40

LIST OF FIGURES - CONTIUNED

4.6	Average EMG/Torque ratio for the 'incliners' and 'decliners' during the fatigue protocol.....	41
4.7	Average distance (m) for the strength-trained (n = 9) and endurance-trained (n = 11) groups for the 3-Forward hops test. Group differences were significant (< 0.001).....	44
4.8	Average time (s) for the strength-trained (n = 10) and endurance-trained (n = 11) groups for the Figure-8 hop test.....	45
4.9	Average time (s) for the strength-trained (n = 9) and endurance-trained (n = 10) group for the M/L hop test. Pre- and post-fatigue hop tests were significantly different (< 0.001).....	46
4.10	Average time (s) for the strength-trained (n = 10) and endurance-trained (n = 11) for the Up/Down hop test. Significant differences (0.011) between the pre- and post-fatigue tests.....	46

ABSTRACT

Results of preliminary data collection indicate an increase of electromyography (EMG) amplitude in fatiguing isokinetic contractions of the knee extensors. The primary purpose of this study was to determine if the EMG/Torque relationship of vastus lateralis changes as a result of fatigue. The second purpose of this study was to determine if tests of functional ability are affected by fatigue. Twenty-two subjects (13 males and 9 females) were sampled from two populations with different types of training (strength versus endurance) experience. The procedures included a five-minute self-selected warm-up on a cycle ergometer, pre-fatigue functional ability tests, fatigue protocol and post-fatigue functional ability tests. The functional ability test protocol included four single-leg hopping drills to assess the functional performance of the knee joint. Torque was measured on an isokinetic dynamometer at 60 degrees per second through a functional range of motion until acute fatigue was reached during the fatigue protocol. Surface EMG electrodes were placed over the vastus lateralis to develop an EMG/Torque ratio during the dynamic contractions. The results indicate training type did not significantly affect torque production ($p = 0.373$) or the EMG/Torque ratio ($p = 0.744$) during isokinetic knee extensions in response to acute muscular fatigue. The strength-trained sample tended to have a greater increase of the EMG/Torque ratio during the fatigue protocol. The results did indicate that there were two significantly different types of response to acute muscular fatigue ($p < 0.001$). There were significant differences between the pre- and post-fatigue functional ability tests for the M/L ($p < 0.001$) and Up/Down ($p = 0.011$) but not for 3-Forward ($p = 0.408$) or Figure-8 ($p = 0.286$). One group doubled their activation magnitude during the fatigue protocol, while another group did not increase their activation magnitude during the fatigue protocol. It is possible that the increase of activation magnitude seen during the fatigue protocol is a result of transition of fiber type utilization. Further study is needed to determine what is the primary cause of the muscle's response to acute muscular fatigue.

CHAPTER ONE

INTRODUCTION

Development of Problem

Tired and fatigued workers sustain overuse injuries that can develop into musculoskeletal disorders (MSD). Musculoskeletal and cumulative trauma disorders (CTD) are physical injuries that develop over a period of time as a result of repeated biomechanical or physiological stresses (Fernandez & Marley, 1998). The effects of CTDs are widespread and costly. Fifteen to twenty percent of Americans experience CTDs each year as the result of fatigue (Melhorn, 1996). Twenty billion dollars are spent each year treating MSDs that result from fatigue (Pasacerelli, 1994). Overuse injuries are often associated with manual labor, but laborers are not the only population affected by CTDs. Fatigue also affects recreational, habitual, and professional athletes, with fatigued athletes being more susceptible to serious injury. Anterior cruciate ligament (ACL) rupture and other traumatic joint injuries are more likely to occur when athletes become fatigued. Each year 80,000 Americans tear their ACL's costing the American economy an estimated one billion dollars per year to treat ACL injuries (Griffin et al., 2000). Thus, developing a better understanding of the onset and effects of fatigue could help prevent unnecessary injuries and reduce the associated costs.

Currently, it is known that fatigue may lead to development of MSDs, but there is a lack of knowledge regarding the precise dose-response of repetitive movement and exertion that leads to specific injuries. By developing a better understanding of fatigue,

researchers may be able to develop effective prevention of CTDs from muscular fatigue (Asmussen, 1979).

Background

Fatigue is defined as the constant decrease of performance capacity of muscles during physical activity (Asmussen, 1979). Quantifying muscular fatigue can be difficult, but measuring the electrical activity of muscle tissue is a safe, efficient, and effective method of assessing changes in muscular performance. Thus, assessing the activation magnitude of stimulated muscle fibers can be a reasonable measure of muscular capacity (Ray & Guha, 1983). Electromyography (EMG) amplitude measures the electrical activity of contracting muscle by summing the potentials of the motor units that are stimulating the muscular tissue (Cogshall & Bekey, 1970). An effective way of measuring muscular fatigue is the ratio of electrical stimulation to the force produced (EMG/force relationship) (Eguchi, 2004). The amplitude of EMG signal should be proportional to force production. This relationship is commonly referred to as the EMG/force relationship.

Researchers have provided conflicting models for quantifying changes of EMG amplitude in relation to force production as a result of muscular fatigue. Some authors have found that a linear model is the best fit (Alkner, Tesch, & Berg, 2000; Onishi et al., 2000; Pincivero, Dixon, & Coelho, 2003b), while others have indicated that the EMG/force relationship is best described by non-linear models (Hakkinen & Komi, 1983). It has been postulated that the differences in the EMG/force relationship are a result of the physiological characteristics of muscle tissue being tested (Bigland-Ritchie,

1981). Comparing the EMG/force ratio produced by an anaerobically-trained sample versus an aerobically-trained sample during fatiguing isokinetic knee extensions may give us insight into whether it is physiological characteristics of type I and type II muscle fibers that cause differences in the EMG/force relationship.

For studies of the EMG/Torque relationship the muscle, type of contraction, angle of contraction, speed of contraction and EMG electrode placement all need to be appropriately controlled. Standardization of joint angle and speed of contraction is important because changes of both directly affect EMG amplitude (Kawakami, Kubo, Kanehisa, & Fukunaga, 2002). Electromyography amplitude increases with contraction velocity. Slower contractions allow the muscle cells to produce more force with less activation. Muscular tissue has an optimal length for force production and changes in the joint angle alter the length-tension relationship. Discrepancies of muscle, type of contraction, angle of contraction and speed of contraction utilized by previous researchers on the EMG/force relationship have made the application of their findings difficult to interpret.

The simplest and most effective way to study fatigue is to quantify the relationship between EMG amplitude and joint torque (Bigland-Ritchie, 1981). Exactly how the EMG/Torque relationship responds during fatiguing contractions remains unclear.

Previous researchers have introduced functional ability tests as an alternative method of testing fatigue (Augustsson, Thomee, & Karlsson, 2004; Itoh, Ichihashi, & Sakamoto, 1989). Previous authors have suggested use of these dynamic functional ability tests as effective methods of analyzing the performance capacity of fatigued joints.

The previous literature on functional ability tests concluded that the best method of testing fatigue was to use the ratio of EMG/Torque relationship as the primary indicator of the effects of fatigue with the results of functional ability tests as a secondary measure (Doorenbosch & Harlaar, 2003).

Statement of Purpose

Researchers interpreted an increase of EMG amplitude in fatiguing isokinetic contractions of the knee extensors from the results of preliminary data collection. The primary purpose of this study was to determine if the EMG/Torque relationship of vastus lateralis changes as a result of fatiguing isokinetic knee extension contractions. The second purpose of this study was to determine if the functional ability tests are affected by fatiguing isokinetic knee extensions.

Aims of the Study

The aims of this study were to measure and compare differences of the EMG/Torque relationship for the vastus lateralis between two populations (anaerobically trained and aerobically trained) and to measure the effects of acute muscular fatigue on the functional ability of the knee joint for college-aged populations.

Primary Hypothesis

It was hypothesized that the EMG/torque ratio will increase more for the anaerobically trained sample versus the aerobically trained sample.

$$H_{01}: \mu_1 = \mu_2$$

$$H_{a1}: \mu_1 > \mu_2$$

The notations μ_1 and μ_2 represent the population means of the EMG/torque ratio for the anaerobically trained and the aerobically trained individuals, respectively.

Secondary Hypothesis

It was also hypothesized that the performance of the post-fatigue functional ability tests would be worse than the pre-fatigue values for all college-aged populations.

$$H_{02}: \mu_1 = \mu_2$$

$$H_{a2}: \mu_1 < \mu_2$$

The notations μ_1 and μ_2 represent the population means of the measures collected for the pre- and post-fatigue functional ability tests.

Tertiary Hypothesis

It was also hypothesized that the difference in the measures collected during the functional ability test between pre- and post-fatigue would be significantly different between populations

$$H_{03}: \mu_{1\text{post-pre}} = \mu_{2\text{post-pre}}$$

$$H_{a3}: \mu_{1\text{post-pre}} \neq \mu_{2\text{post-pre}}$$

The notations μ_1 and μ_2 represent the population mean difference of the values between pre- and post-fatigue collected during the functional ability test for the two different populations: anaerobically trained and aerobically trained individuals.

Assumptions

It was assumed that all the college-aged subjects were in good health at the onset of the study. It was assumed that the daily activities of life would not affect performance

during testing. Also, it was assumed that the subjects were representative of their selected populations.

Limitations

The study will be limited because samples included athletes, which may reduce the generalizability of the study findings to the general population.

Operational Definitions

The following definitions were adopted for the purposes of this study:

Acute Fatigue: when peak torque produced during the concentric phase of knee extension falls below 50 % of maximal isometric voluntary contraction for two consecutive attempts.

Concentric: muscle contraction that develops tension and shortens in length.

Eccentric: muscle contraction that develops tension and increases in length.

Electromyography: measurement of the electrical activity of activated muscle motor units.

EMG/Torque relationship: ratio of the electrical activity of a specific muscle and the torque produced at a respective joint.

Extension: joint movement where the relative angle between adjacent limb segments increases as the joint returns to anatomical position.

Fatigue: transient decrease in performance capacity due to physical activity.

Flexion: joint movement where the relative angle between adjacent limb segments decreases as the joint moves away from anatomical position.

Isokinetic Contraction: muscular contraction where the speed of joint movement remains constant.

Isometric Contraction: contraction where muscular tissue produces force but joint position does not change.

Maximal Voluntary Contraction: the maximal amount of force exerted by a muscle during an isometric contraction as measured by joint torque.

Muscular Fatigue: physiological inability of muscular tissue to maintain required force levels for a given activity level.

Muscular Force: amount of tension produced by muscular tissue.

Torque: product of force applied and the perpendicular distance from point of application to the axis of rotation.

CHAPTER TWO

LITERATURE REVIEW

Introduction

Fatigue during occupational, ergonomic and athletic situations can be hazardous, potentially resulting in CTDs (Gerdle, Karlsson, Crenshaw, & Friden, 1997). Cumulative trauma disorders such as pulls, strains, and fractures, often occur when individuals become fatigued. The effects of CTDs are widespread and costly. Approximately 15 to 20% of Americans experience CTDs each year as a result of the traumatic effects of fatigue (Melhorn, 1996). In 1993, 20 billion dollars were spent treating injuries and illness that occurred from people's inability to function properly when tired (Pasacerelli, 1994). A greater understanding of fatigue may help prevent needless injury that can occur from a loss of performance capacity. To analyze the effects of fatigue, researchers have analyzed the changes of the relationship between the level of activation of muscular tissue and the resultant torque production during fatiguing contractions. This EMG/Torque relationship provides insight into the effects of fatigue on muscular tissue in a controlled laboratory setting. To determine the effects of fatigue in athletic situations researchers have developed dynamic experiments that simulate conditions encountered in athletics, to evaluate the functional ability of joints. It has been suggested that dynamic tests are best at evaluating the functional capacity of a joint when tested before and after fatigue (Augustsson et al., 2004).

This chapter reviews the effects of acute muscular fatigue upon the functional ability of the knee joint. First, the review covers the mechanisms of fatigue that create

declines in performance. Next, the use of electromyography as a quantifiable measure of muscular capacity and the factors that affect muscle force production are discussed before descriptions of the current theories regarding the EMG/Torque relationship are mentioned. The consequence of fatigue upon accepted theories of the EMG/Torque relationship is reviewed and finally, recent attempts at creating dynamic tests to analyze the functional ability of joints are discussed.

Fatigue

Muscular fatigue has been defined as the physiological inability to maintain force or work levels (Asmussen, 1979; Bigland-Ritchie, 1981; Mannion & Dolan, 1996). Muscle fatigue results from physical activity that causes a transient decrease in the ability of muscle tissue to produce force. To this date, researchers have identified two types of fatigue: central and peripheral fatigue. Central fatigue is the inability of the central nervous system (CNS) to properly conduct electrical stimulus to the motor neurons for muscular contraction. Peripheral fatigue is failure of the contractile components of muscle tissue. It is still unclear as to which type of fatigue causes the decrease of muscular performance during physical activity. It may be that both central and peripheral fatigue act simultaneously to inhibit the performance capacity of the subject (Kawakami, Amemiya, Kanehisa, Ikegawa, & Fukunaga, 2000; Schillings, Hoefsloot, Stegeman, & Zwarts, 2003). During isometric maximal voluntary plantar flexion both peripheral and central fatigue were observed by measuring resting twitch amplitude and level of activation (Nordlund, Thorstensson, & Cresswell, 2004). Nordlund et al. (2004) found that level of activation correlated positively with central fatigue and decreased 12.6 %,

while resting twitch amplitude correlated positively with peripheral fatigue and decreased 16.2 % during isometric contractions. Thus, during isometric contractions both peripheral and central fatigue are evident.

Central fatigue occurs in the CNS proximal to the motor neurons, in the spinal cord or brain. It has been postulated that central fatigue transpires from inhibition of voluntary effort. Voluntary effort is hindered by the nerve afferents, which innervate the inhibitory part of the reticular formation, lowering arousal (Asmussen, 1979). Asmussen indicates that the lower arousal level associated with central fatigue arises from a lack of training. A trained individual will not experience lower arousal as soon or as often as an untrained individual. Thus, central fatigue could be overcome with training and would not play a role in the decreased performance capacity of muscular tissue with proper conditioning.

Previous researchers, Behm and St-Pierre (1997), indicate that central fatigue resulting in lower activation levels of muscular tissue may be a result of the duration of contraction. Long, slow contractions resulting in extended periods of physical activity before the onset of fatigue created greater decrease in muscle activation than short, explosive exercise periods. According to Behm and St-Pierre, the duration of exercise plays a large role in the type of muscular fatigue that inhibits performance. In an attempt to delay fatigue, the body relies on fatigue-resistant type I muscle fibers by stimulating an inhibitory signal (central fatigue) (Hug et al., 2004). The inhibitory signal prevents the high-force, quick-fatigue type II muscle fibers from contraction during long durations of work. Thus, a subject's level of training would greatly affect the ability to maintain workloads required for desired activity and the type of fatigue they encounter.

If properly trained, central fatigue would not be accountable for performance declines, but rather peripheral fatigue would be primarily responsible for the decline of muscle performance during physical activity. Peripheral fatigue occurs distal to motor neurons within the motor units, and can involve the motor endplates, peripheral nerves and contractile properties of muscle fibers. The accumulation of fatiguing substances, catabolites, and the depletion of essential contraction substrates, such as creatine phosphate, adenosine triphosphate (ATP), and calcium can all play a role in peripheral fatigue. There are two postulated methods of peripheral fatigue: transmission and contractile failure. Inabilities of the neuromuscular junction, muscle membrane or endoplasmic reticulum to properly conduct the electrical stimulation are sites of transmission failure during peripheral fatigue. The lack of essential substrates or accumulation of contraction inhibiting substances inside the muscle cells may lead to malfunction of the muscle filaments, which in turn causes localized contraction failure (Asmussen, 1979).

Previous researchers have attempted to quantify the contributions of central and peripheral factors of fatigue (Schillings et al., 2003). Researchers tested subjects during maximal sustained voluntary isometric contractions (MVC) of the biceps brachii. The testers used superimposed electrical stimulation of the biceps brachii to calculate central fatigue, using the amplitudes of the superimposed force normalized with voluntary force collected by a dynamometer. The value of the superimposed force was represented as central activation failure (CAF). The authors found a significant increase of CAF (18.1 to 39.8 %) during the MVC, even though not all subjects experienced an increase in CAF. Central activation failure indicates a decline in the ability of the neuromuscular system to

recruit new motor units. To calculate the contribution of peripheral fatigue to the decline of force production during isometric MVC, the researchers used muscle fiber contraction velocity (MFCV). Muscle fiber contraction velocity was found to decrease from 5.0 m/s to 2.9 m/s during the MVC (Schillings et al., 2003). The entire decline of MFCV occurred in the first minute of contraction. Schillings et al. (2003) identified that peripheral fatigue occurred during isometric contractions but failed to distinguish whether it was modifications of metabolic environment and contractile properties of the muscle tissue or decreases in speed of motor unit recruitment that caused the fatigue.

Initially during sustained MVC, peripheral fatigue can include metabolic changes of the intramuscular fluid and contractile failure, allowing performance deterioration. For prolonged contractions, central fatigue does not inhibit performance until the contractile elements of muscle cells have caused a significant decrease in work performance. Thus, peripheral fatigue is a loss of the muscle cells' immediate ability to properly contract but whether this arises from an inability of the electrical stimulation to cross the cell membrane or failure of the contractile components of the muscle cells is still undetermined. Nordlund et al. (2004) determined that peripheral fatigue correlated with level of activation, while Kawakami et al. (2000) found that the declines of peripheral fatigue were due to failure of the contractile components of muscle. The researchers did agree that peripheral fatigue plays a larger role in the decline of force than central fatigue. Schillings et al. (2003) indicated that not all subjects suffered CAF, which reaffirmed the speculation that the decline of force from central fatigue can be diminished through training.

Electromyography

Electromyography (EMG) records the myoelectric signal of muscle fiber recruitment. Myoelectric signal is the algebraic sum of the motor unit action potentials that are stimulating the muscle tissue (Coggshall et al., 1970). The amplitude of myoelectrical signal is a quantifiable measure of muscular capacity; however, it requires substantial signal processing prior to interpretation (Ray et al., 1983).

There are several steps of processing EMG signal for analysis. Rectification is used to create a signal with only positive polarity by taking the absolute value of the original raw EMG signal. Next, to integrate the EMG, the signal can either be standardized (or normalized) over the entire time period of the contraction, to a standard time, or to a preset level. For comparison, the collected information is commonly standardized as a percentage of standard contractions (Bigland-Ritchie, 1981). Normalizing the EMG signal accounts for inter-individual differences in conduction that can exist.

To gather EMG signal, the researcher can use either surface or intramuscular electrodes. Both electrode types have pros and cons associated with their use. The use of surface electrodes is an easy, painless method of collecting data, but the EMG signal collected from surface electrodes is affected by variations in skin resistance and subcutaneous fat (Bigland-Ritchie, 1981). Surface EMGs are also prone to collecting “crosstalk”. Crosstalk occurs when an EMG electrode collects unintended electrical activity from muscles that are not being studied. Indwelling electrodes, on the other hand collect a cleaner signal, however they require the invasive process of needle insertion. Researchers suggest intramuscular EMG is not as reliable as surface electrodes during

dynamic movements. Pease and Elinski (2003) demonstrated that surface EMG produced better reliability for the vastus lateralis than intramuscular electrodes during isokinetic knee extensions.

Force

The amount of force produced by a muscle is influenced by other factors beyond simple electrical activation. Other factors that affect force production include: type of motor unit recruited, cross sectional area of muscle, muscle length at the beginning of activation, angle of the joint, and rate of actin and myosin ATPase activity. Muscle physiologists have developed a thorough understanding of these principles that affect force production generating length-tension, force-velocity and torque-angle curves (Bigland-Ritchie, 1981).

The length-tension relationship of muscular tissue indicates that the amount of force produced by contracting muscles is dependent on the length of the fiber relative to its optimal length. Force production relies upon the activation of the cross-bridge cycle of muscle tissue. If the muscle is too short or too long, then maximum force development is impaired. Tension development is restricted because the actin and myosin heads of the muscle fibers have difficulty forming cross-bridges when the muscle is too compacted or too stretched (Gillard, Yakovenko, Cameron, & Prochazk, 2000). Researchers have confirmed that muscle length has a significant effect on the amount of maximal force that can be produced during isometric, concentric and eccentric contractions (Klass, Guissard, & Duchateau, 2004; Komi, Linnamo, Silventoinen, & Sillanpaa, 2000; Miyamoto & Oda, 2003).

Muscle fibers have an optimal length and velocity for force production (Hill, 1938). The force-velocity relationship shows that the slower the concentric contraction, the greater the force potential. For eccentric contractions however, the greater the velocity of the movement, the greater the force produced (Wickiewicz, Roy, Powell, Perrine, & Edgerton, 1984).

The effects of length and velocity on force capacity of the muscle can be explained by physiological characteristics of the muscle, but an understanding of biomechanics is needed to elucidate the effect of joint angle on torque capabilities. Force is transferred to the bone through the muscle's tendinous insertion. The angle of insertion into the bone is affected by the angle of the joint the muscle crosses. At the optimal angle, the moment arm of the tendon's insertion is maximized, allowing a greater percentage of the force to be transmitted perpendicular to the bone, producing greater torque about the joint (Rassier, MacIntosh, & Herzog, 1999).

The EMG/force Relationship

It has been suggested that if the muscle examined and type of contraction are carefully controlled, smoothed rectified or integrated EMG signal of human muscle should be able to document the EMG/force relationship well (Bigland-Ritchie, 1981). Previous authors indicated that the EMG/force relationship could be explained in four different ways the amplitude of EMG signal could increase linearly with force, non-linearly, in a quadratic fashion or with a biphasic pattern (Metral & Cassar, 1981). Many researchers have found a linear EMG/force relationship in the vastus lateralis (Alkner et al., 2000; Onishi et al., 2000; Pincivero et al., 2003b).

Researchers suggest that the physiological properties of individual muscles dictate what type of model will most aptly fit the relationship. Alkner et al. (2000) indicated that the EMG/force relationship of the vastus lateralis was linear, but the EMG/force relationship of the vastus medialis and rectus femoris deviated from linearity. The non-linear relationship of the vastus medialis and rectus femoris was also found in a previous study by researchers Hakkinen et al. (Hakkinen et al., 1983). It has been speculated that a non-linear pattern of EMG/force is associated with testing of type II muscle fiber, whereas a linear pattern corresponds with type I muscle fibers (Bigland-Ritchie, 1981). If true, then the EMG/force relationship of the vastus lateralis should be non-linear, as the vastus lateralis has been reported to contain 65% type II fibers for an untrained population (Gerdle et al., 1997). Thus, fiber-type may not be the primary determinant of the EMG/force relationship.

The amplitude of EMG increases with greater contraction intensity for all types of contraction (McHugh, Connolly, Eston, & Gleim, 2000; McHugh, Tyler, Greenberg, & Gleim, 2002; Potvin, 1997). The length-tension relationship states that eccentric contractions allow the muscle to produce more force than concentric contractions but the EMG/force relationship is significantly different for eccentric contractions versus concentric contractions. Researchers indicate a significantly greater increase of activation level during concentric contractions than during eccentric contractions for similar increases in force (Babault, Pousson, Ballay, & Van Hoecke, 2001; McHugh, Connolly, Eston, Gartman, & Gleim, 2001). This difference can be credited to the ability of muscle to produce more force without an increase in the number of motor units activated for eccentric contractions. The series and parallel elastic components of the

tendon and fascial tissue allow creation of passive tension. Passive tension accounts for the ability of muscle tissue to create more force during eccentric contractions by summing passive and active tension.

In addition to type of contraction, the level of activation is affected by velocity of movement. In order to maintain adequate force production throughout an entire range of motion the level of activation needs to rise with increases of velocity due to the force-velocity curve. If a movement is too fast the measurement of EMG can become saturated with no discernible differences of activation, distorting the EMG/Torque ratio (Tate & Damiano, 2002). It has been shown that increased angular velocity up to $140^{\circ}/s$ exhibits noticeable increases in EMG amplitude (Potvin, 1997). Additionally, recent authors demonstrated that neural drive of concentric contractions is consistent with angular velocity up to $120^{\circ}/s$ but may become inconsistent at velocities greater than 140° per second (Babault, Pousson, Michaut, Ballay, & Van Hoecke, 2002).

Researchers have failed to find significant differences for force production between genders but the level of activation differs significantly between genders (Hunter, Critchlow, In-Sik, & Enoka, 2004; Wretling & Henriksson-Larsen, 1998). When males and females were matched for maximal force production the female's activation levels and EMG/force relationship were significantly different than for males. Male's EMG/force relationship decreased more than females during fatiguing contractions (Lindstrom, Karlsson, & Gerdle, 1995). Also, women showed a greater increase of EMG burst when fatigued than men (Hunter et al., 2004). During fatigue women were able to recruit more motor units than men but were unable to recruit as many muscle fibers as men pre-fatigue. The effects of fatigue appear to be less detrimental on the capacity of

women's muscular tissue to produce force than men's. Thus, gender does not appear to affect the amount of force that can be produced but does significantly affect the responses of the muscular tissue to fatigue.

The Effects of Fatigue on the EMG/Force Relationship

Recent researchers have indicated that the EMG/force relationship is biphasic, with an initial linear relationship before a breakpoint that drastically changes the slope of the relationship. Crenshaw et al. (2000) and Metral et al. (1981) concluded that the general relationship of EMG/force was the sum of two increasing exponentials. The breakpoint and change of the slope of the EMG/force relationship could represent a threshold, representing the onset of fatigue. Another explanation of the biphasic relationship could be a change of reliance on muscle fiber type. Fast twitch muscle fibers have a greater susceptibility to fatigue than slow twitch fibers, thus during short, quick exercise the amplitude of EMG increases in an attempt to recruit more fast twitch motor units to help perform the muscular contractions. When the duration of exercise continues for extended periods of time an inhibitory sensory signal occurs, effectively switching reliance of muscular tissue from fast twitch to slow twitch fibers (Komi & Tesch, 1979).

In conclusion, EMG has become a widely accepted measure for quantifying the capacity of muscular tissue. Researchers have recently used EMG to gain a greater understanding of muscular fatigue. Currently, there are still many gaps in the literature on EMG, with little documentation of EMG/force relationship as related to fatigue. More research is needed to ascertain the true EMG/force relationship. Investigating how the

EMG/force relationship relates to fatigue will provide a better understanding of how muscle fatigue affects joint function.

Functional Tests

Researchers have conducted numerous studies on functional tests of the knee joint with the purpose of identifying dynamic tests that adequately assess the functional ability of the lower limbs. The ability to accurately assess limitations of the lower limbs allows physical therapists and athletic trainers to have a better understanding of when an athlete in rehabilitation is ready to return to full activity.

Functional tests can also be used in research to assess the effects of muscular fatigue on joint performance. Previous researchers used tests such as single-leg hopping and shuttle runs to examine the lower limbs' sensitivity to dynamic testing (Noyes, Barber, & Mangine, 1991). The authors demonstrated that some functional tests have low sensitivity in detecting lower limb limitations when compared with single-leg hop drills. The inability of the shuttle run and vertical jump tests to detect limitations of the lower limb could be attributed to the nature of the assessments. Both the shuttle run and vertical jump were tested using multiple legs rather than focusing on a single leg test. It could be that single leg tests have higher reliability in determining the functional ability of the lower limb.

During a battery of functional tests that consisted of four different single-leg hop drills it was found that 95 % of a normal, healthy control population has symmetrical function, while only 18 % of anterior cruciate ligament (ACL) deficient subjects could obtain symmetry for all four tests. Abnormal symmetry between normal and ACL

deficient knees was identified 42 to 68 % of the time depending on the type of single-leg hop tested (Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998). In another study, 62 % of an ACL deficient population performed abnormally on at least one of two single-leg hop tests (Barber, Noyes, Mangine, McCloskey, & Hartman, 1990). Other researchers concluded that the single-leg tests of a single hop and timed distance hop were good for determining the functional performance of the lower limb (Noyes et al., 1991). The researchers suggested that testing for functional limitations can be sufficiently achieved with two or more single-leg hopping tests. Subjects may be able to perform normally on one single-leg hop tests but by testing the knee function in several different ways the probability of identifying weakness or vulnerabilities in the knee increases.

Fatigue has a large effect on the functional performance of an ACL deficient knee. In a study of 19 subjects that exhibited normal single-leg hop symmetry with an ACL deficiency, 68 percent of the subjects showed abnormal hop symmetry after a fatiguing protocol (Augustsson et al., 2004). Thus, the authors suggested that all functional testing of the knee joint should be performed pre- and post-fatigue in order to ensure reliable comparison. Due to the effect that fatigue can have on the normal function of a knee with a structural deficiency the results of dynamic testing can be compromised by inability to control for fatigue. Based on these findings, it appears the same functional tests used to assess the functional ability of an ACL deficient knee may be proficient for assessing the effects that fatigue has on the knee.

Recent researchers attempted to use both the EMG/force relationship and a dynamic functional ability test to measure differences between normal and ACL deficient knees (Doorenbosch et al., 2003). The authors found that the EMG/force model provided

a sufficient estimate of net joint moments produced by both normal and deficient knees, but the authors utilized a vertical jump test as the functional ability test rather than multiple single-leg tests. The next step after Doorenbosch and Harlaar's research would be to use the EMG/force relationship along with multiple single-leg tests to test the functional ability of the knee joint.

In conclusion, EMG is an acceptable measure of muscle capacity, which can be used to calculate the rate of fatigue. With an understanding of fatigue, researchers can help prevent injury that occurs from a loss of performance capacity. To this date, researchers have used EMG to identify two types of fatigue that can occur from exhaustive exercise: central and peripheral. It appears from previous research that the combined effect of central and peripheral fatigue is involved in the transient decline of muscle performance capacity, but it has been suggested that peripheral fatigue plays a larger role in the performance decline.

The EMG/force relationship has been accepted as a satisfactory method of studying neuromuscular fatigue. The EMG/force relationship can provide insight into muscular fatigue but does not provide a clear understanding of the functional capacity of joints affected by fatigue. Dynamic tests have been developed to simulate athletic situations to test the functional ability of joints. Previous research indicates that single-leg hop tests correlate well with the functional ability of the knee joint.

By carefully documenting the EMG/force relationship in the knee musculature and developing a battery of single-leg hop tests that are sensitive to muscle fatigue these measures may provide further insight into the effects of muscle fatigue on the functional ability of the knee joint.

CHAPTER THREE

METHODOLOGY

Subjects

Twenty-two subjects (13 males and 9 females) from the campus of Montana State University volunteered to participate in the study. The age of the subjects ranged from 18 to 29 years (mean \pm SD: 22.4 \pm 2.8), mean weight was 77 \pm 21.2 kg, mean height was 175.8 \pm 10.9 cm. Eleven participants from two populations with different types of training experience were sampled. Training experience was determined from responses to a simple activity questionnaire (Appendix B). Sample A was selected based on their level of anaerobic training. Subjects were included in sample A if they regularly measured their strength performance but not their endurance performance. Sample B was selected based on their level of aerobic training. Subjects were included in sample B if they regularly measured their endurance performance but not their strength gains. Average age, height and weight for both samples are shown in Table 3.1. Subjects were excluded from involvement in the study if they had a history of knee injury or chronic pain in their dominant leg (eg. ACL rupture or chronic tendonitis), or a history of neuromuscular dysfunction in the lower extremity that would affect motor performance. All subjects signed an Internal Review Board (IRB) approved informed consent prior to their involvement in the study (Appendix A).

Procedures

The procedures included a five-minute self-selected warm-up on a cycle ergometer, pre-fatigue functional ability tests, fatigue protocol and post-fatigue functional

ability tests. Next, will be a detailed description of the procedures.

Table 3.1: Demographic and anthropometric data of the sample: Mean (SD).

	n	Age	Mass (kg)	Ht. (cm)
Total	22	22.4 (2.8)	77 (21.2)	175.8 (10.9)
Strength	11	21.6 (1.4)	93.6 (16.5)	181.7 (8.1)
Endurance	11	23.1 (3.6)	60.4 (8.3)	169.9 (10.4)

Pre-fatigue Functional Ability Tests

First, the subjects warmed up for 5 minutes on a cycle ergometer. Next, the testing procedure began with subjects performing a battery of functional tests (FT) on their dominant leg to establish a baseline of functional performance. Leg dominance was defined as the leg with which they generally chose to kick a ball. The FT protocol included four single-leg hopping drills to assess the functional performance of the knee joint. During the FT, subjects were asked to perform two trials of each of the following tests on only their dominant leg (measured parameter in parentheses):

- three consecutive forward hops (total distance covered)
- figure eight hops (time taken to complete two consecutive cycles)
- up/down hops (time taken to complete 20 repetitions up on to and down from a 20 cm box)
- medial/lateral hops (time taken to complete 10 medial-lateral cycles over a 30 cm gap)

Each subject was allowed one minute between each trial and test of the functional ability test. The hops are depicted in Figures 3.1 through 3.4.

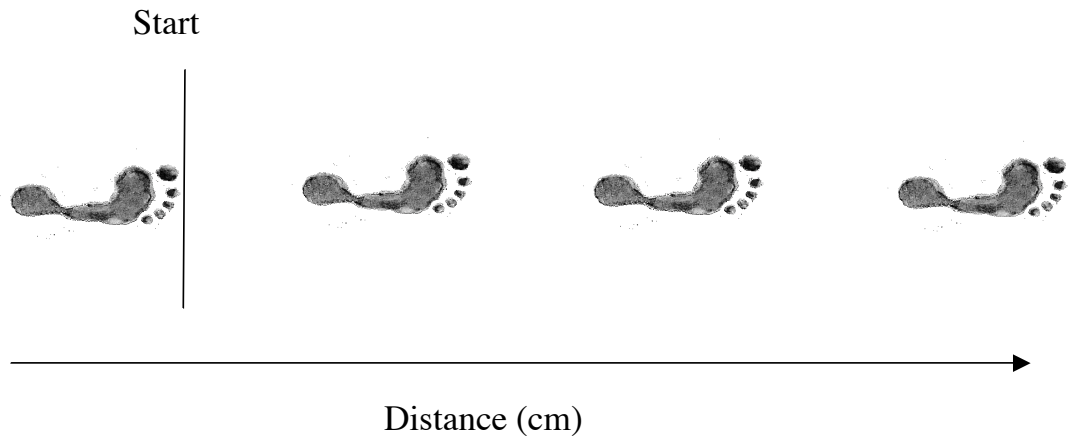


Figure 3.1: A diagram of the 3-forward consecutive hop functional ability test.

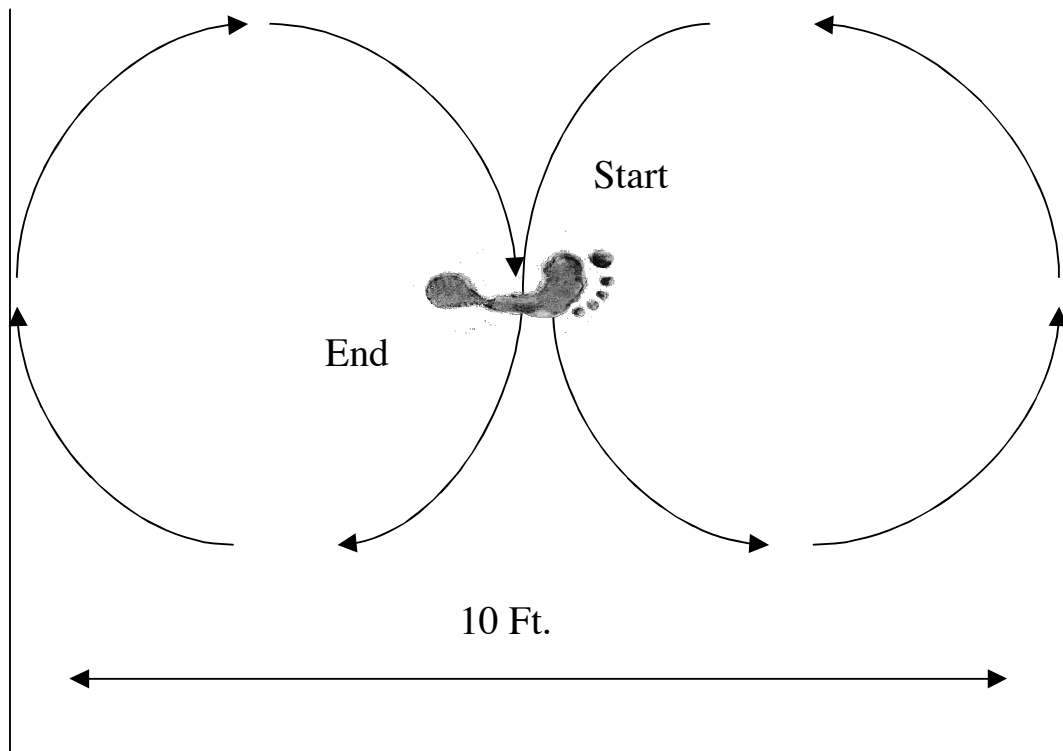


Figure 3.2: A diagram of the Figure-8 hop functional ability test.

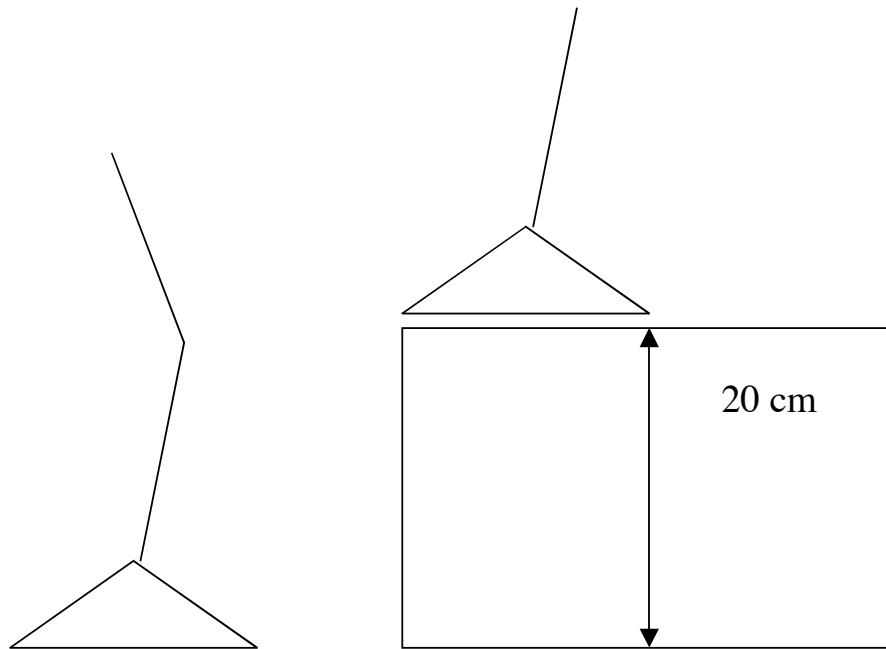


Figure 3.3: A diagram of the Up/Down hop functional ability test.

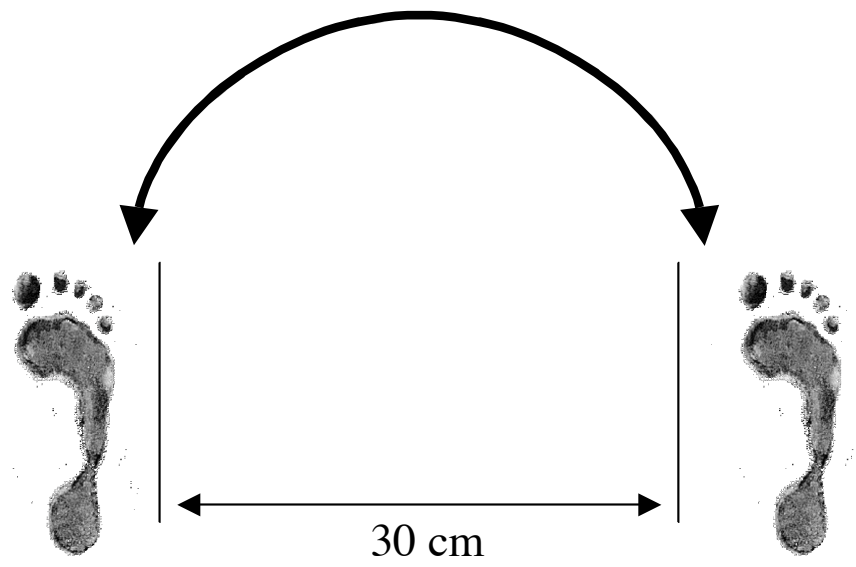


Figure 3.4: A diagram of the M/L hop functional ability test.

The order of individual tests was randomized for each subject and counterbalanced between groups. Time and distance values collected during the second trial of each functional test were compared between pre- and post-fatigue measures. The second trial was used because previous research has shown a rapid familiarization effect with single-leg hops (Augustsson et al., 2004).

Fatigue Protocol

After completion of the FT, subjects were allowed to familiarize themselves with the strain-gauge dynamometer before performing three isometric maximal contractions of the knee extensors with the dominant leg. During the isometric contractions, knee angle was maintained at 45°. This angle was selected because the length of the knee extensors should correspond to the optimal length for force production, making it more likely that the “true” maximum contraction will be recorded.

During all contractions, surface EMG amplitude was recorded from the skin overlying the vastus lateralis (VL). The bi-polar electrodes were placed one hand's breadth (approximately five inches) superior to the patella, over the belly of the VL muscle. The skin was prepared by cleaning with an alcohol swab before applying the electrode to remove any lotion or residue that may reside on the skin. To locate the VL for electrode placement the subjects were asked to contract their knee extensors so that the investigator could palpate the VL. The VL muscle was chosen to represent the knee extensor group because it is greatly affected by velocity and has greater activation magnitudes than other knee extensors during knee extension (Kawakami et al., 2002; Pincivero, Coelho, Campy, Salfetnikov, & Suter, 2003a). The EMG amplitude of the VL

also has the highest reproducibility of the three surface quadriceps muscles (Larsson et al., 1999).

After isometric testing was completed, subjects were asked to perform maximally during isokinetic knee extension (KE) at $60^{\circ}/s$ with their dominant leg. During isokinetic contractions, the knee extensors were active through each subject's entire functional range of motion. Subjects were verbally encouraged to perform with maximal effort. The isokinetic contraction can be divided into two phases: concentric and eccentric. The isokinetic contractions were run in sets of ten with a five second break in between sets until acute fatigue of the leg occurred. Acute fatigue was defined as when the peak torque production of the concentric phase during the maximal isokinetic KE decreased below 50% of the subject's MVC for two consecutive repetitions. The velocity of $60^{\circ}/s$ was chosen due to recent findings that peak torque decreases as velocity increases (Kawakami et al., 2002). In addition contractions at $60^{\circ}/s$ allow the subject to maintain high levels of torque longer than other velocities (Perry-Rana et al., 2002).

During all isometric and isokinetic contractions, subjects were seated on the dynamometer with a hip angle of approximately 90° . Velcro straps were used to secure the subject's thigh and waist to the dynamometer and to keep the knee joint aligned with rotation center of the dynamometer. The shank of the dominant leg was secured to the lever arm and the force transducer of the dynamometer was located just proximal to the ankle of the subject (Figure 3.5).

Post-fatigue Functional Test

After completion of the isokinetic contractions, subjects performed a second

battery of FT to assess the effects of acute muscular fatigue upon the functional ability of the knee joint. Subjects were given no more than one minute before beginning the post-fatigue FT after completing the fatigue protocol. All subjects performed the FT in the same order as conducted during the pre-fatigue FT. Parameters measured during the post-fatigue hop drills were compared with pre-fatigue values.



Figure 3.5: Setup of leg to lever arm and force transducer of the KIN-COM dynamometer.

Instrumentation

Strain-gauge Dynamometer

All knee extensor torques for the isometric and isokinetic contractions were measured using an isokinetic strain gauge dynamometer with a sampling frequency of 100 Hz (KIN-COM KC125E Plus, Rehab World, Hixson, TN). The dynamometer measured the amount of force produced by the knee extensors during contraction through a force transducer attached to a lever arm. The distance of the force transducer from the axis of rotation of the knee joint was the length of the lever arm. The amount of torque produced was calculated by multiplying the force value by the lever arm. The result (in Nm) is the net torque produced about the knee joint.

EMG Recording System

A passive bi-polar surface EMG recording system (Myopac Jr., Run Technologies, Laguna Hills, CA) with Blue Sensor surface electrodes (Ambu, Denmark) was used to collect the activation magnitude of the VL muscle during force production. The sampling frequency of the Myopac Jr. was 1000 Hz with a bandwidth filter between 10 to 1,000 Hz. Vicon Workstation (v4.6, Vicon Motion Systems, Lake Forest, CA) was used to record the EMG activity.

Post-Processing

Graphing force curves of the preliminary data showed that the isokinetic trials could be broken into three linear phases. During the first or “Initial” phase, the subjects maintained 80 to 90 % of isometric MVC for 12 to 15 contractions before force production began to decline. All subjects tested in the preliminary data collection lost the

ability to produce torque in an apparently linear pattern during the second or “Decline” phase. Subjects’ torque production decreased from 80 to 45 % of isometric MVC in approximately 15 contractions. During the third and final phase identified from preliminary data collection, subjects showed signs of acute muscular fatigue but in this “Fatigued” phase they were able to maintain force production. In the fatigued phase subjects produced force at 55 to 45 % of the isometric MVC. Figure 3.6 is an example of torque production during the fatigue protocol.

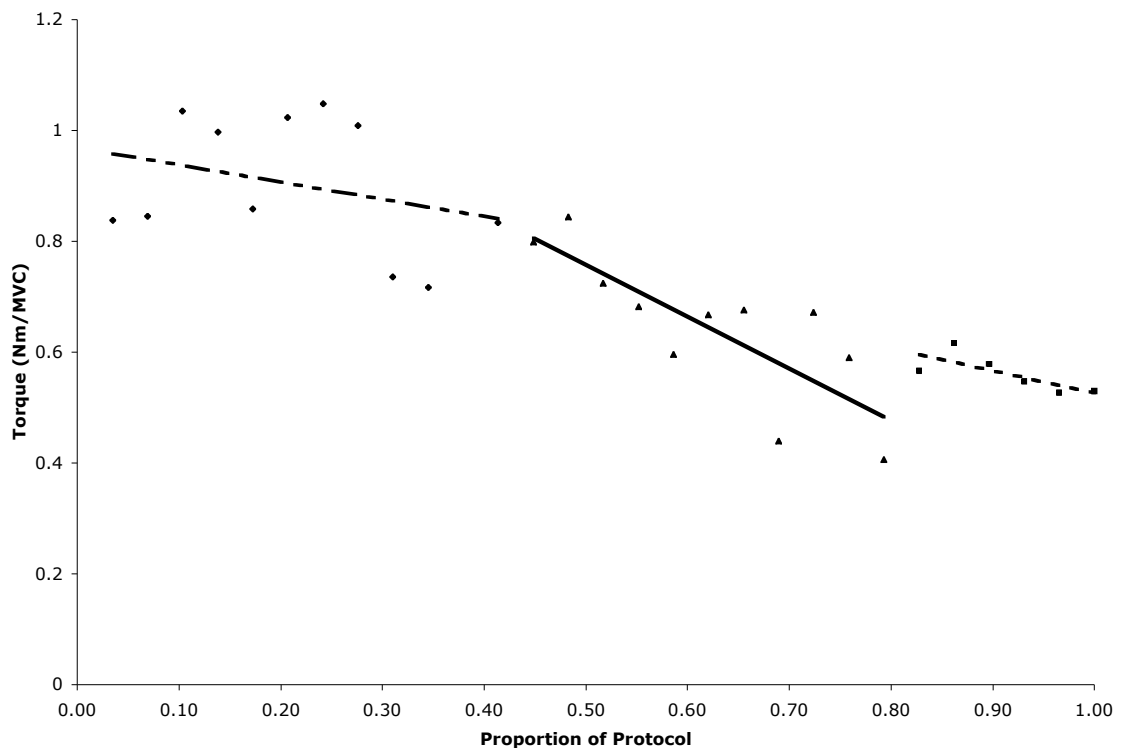


Figure 3.6: An example of a subjects torque production during each phase of the fatigue protocol.

Post-processing of the collected data required calculating torque production and the EMG/Torque ratio during each phase of the fatigue protocol. Torque production of each phase was expressed as a proportion of MVC. To determine the amount of torque

produced during the initial and fatigue phases of the protocol, peak concentric torque production for each contraction of the entire phase was averaged. To obtain the torque production during the decline phase, the peak concentric torque produced during the final contraction of the phase was used.

Before analysis of the EMG/torque relationship the collected EMG signal required signal processing, including full-wave rectification and smoothing with a linear envelope. Rectification takes the absolute value of the original EMG signal and creates a signal that does not cross through zero. A linear envelope was developed by running the rectified signal through a low-pass filter (cut-off frequency of 5 Hz), creating a smoothed, more interpretable curve.

A custom Matlab program (v7.0.1, The Math Works, Inc., Natick, MA) was used to normalize the activation magnitude to the torque produced by the VL and to analyze the ratio of EMG amplitude to torque production during each phase of the isokinetic fatigue protocol. To calculate the mean EMG/Torque ratio, the ratio of each contraction was computed and an average taken for each phase. This provided an EMG/Torque ratio for the conditions of pre-fatigue (initial phase), rate of fatigue (decline phase) and post-fatigue (fatigued phase).

Analysis of the EMG/Torque ratio from preliminary data showed two types of response to acute muscular fatigue during fatiguing isokinetic contractions. One group of responders ('incliners') increased their EMG/Torque ratio during the fatigue protocol to finish the fatigue phase with a ratio approximately 4.0 V/Nm/N, while the second group ('decliners') decreased their EMG/Torque ratio during the fatigue protocol to finish the fatigue phase with a ratio approximately 2.0 V/Nm/N.

Analysis

The dependent variables of this study were the pre- and post-fatigue parameters of the FT and the EMG/Torque relationships of the fatigue protocol. The independent variable was protocol phase. A two-factor analysis of variance (ANOVA) with repeated measures of phase was performed to test for significant differences in the EMG/torque ratio between the phases of the fatigue protocol and between groups. A two-factor ANOVA was also performed with repeated measures of phase to test for significant differences in the EMG/Torque ratio between the phases of the fatigue protocol and between genders. Another two-factor ANOVA with repeated measures of phase was performed to test for significant differences in the EMG/Torque ratio between the phases of the fatigue protocol and between the types of response to acute muscular fatigue. A two-factor ANOVA with repeated measures of phase was performed to test for significant differences in the EMG/torque ratio between the phases of the fatigue protocol and between groups for only the male subjects. The male only ANOVA was run to determine if the gender differences of groups accounted for differences of the EMG/Torque ratio and not the training differences of the groups. A two-factor ANOVA with repeated measures was performed to test for significant group and gender differences between the pre- and post-fatigue measures of each FT parameter. Lastly, a two-factor ANOVA with repeated measures was performed to test for significant group differences between the pre- and post-fatigue measures for each FT parameter for males only.

CHAPTER FOUR

RESULTS

Subject Characteristics

Twenty-two healthy college-aged (13 men and 9 women) participants were sampled. Eleven participants from two populations with different types of training experience were sampled. Training experience was determined from responses on a simple activity questionnaire (Appendix B). Based on their responses to a questionnaire, subjects were placed into one of two groups according to training history (Strength and Endurance trained). Subjects included in the strength-trained sample regularly measured their strength gains but did not measure endurance performance gains. The endurance-trained sample regularly measured their endurance gains but did not measure their strength performance gains. All subjects were compliant with the inclusion and exclusion criteria of this study. Subjects were included if they were aerobically or anaerobically trained. Subjects were excluded if they had a history of knee injury and pain or if they had any neuromuscular dysfunction in the lower extremity that would affect motor performance.

Peak Isometric Torque

The mean peak isometric torque produced was 3.599 +/- 0.860 Nm/Kg for the strength-trained sample and 3.136 +/- 0.549 Nm/Kg for the endurance-trained sample (Table 4.1). There were no significant differences of the peak isometric torque production between the strength and endurance-trained samples when normalized for body mass.

Table 4.1: Peak isometric knee extensor torque normalized to body mass for both samples: Mean (SD).

	n	Pk Torq (Nm/Kg)	p-value
Strength	13	3.6 (0.86)	0.151
Endurance	9	3.1 (0.55)	

Distinguishing Phases of the Fatigue Protocol

During the fatigue protocol the response of the peak torque produced during concentric contractions could be broken into three phases. The first phase (Initial) was typically the first 12 contractions of the fatigue protocol where the subject maintained 80 to 90 % of MVC. The Initial phase lasted approximately 40% of the entire fatigue protocol. The second phase (Decline) was typically 10 to 12 contractions where torque production declined from 80 % of MVC to below 50 % of MVC. The Decline phase lasted through approximately the middle 40% of the fatigue protocol. The final phase (Fatigue) was marked by the final contractions where torque production remained at approximately 50 % of MVC. The Fatigue phase finished the final 20% of the fatigue protocol. Figure 4.1 shows an example of peak concentric torque production during the fatigue protocol.

Isokinetic Torque Production

Knee extensor torque production was calculated during each of the phases of the fatigue protocol. Torque declined from the Initial phase through the Decline phase and remained around 50% of the subjects' MVC for the Fatigue phase of the protocol. Figure

4.2 shows the peak concentric torque production of each subject during all three phases of the fatigue protocol.

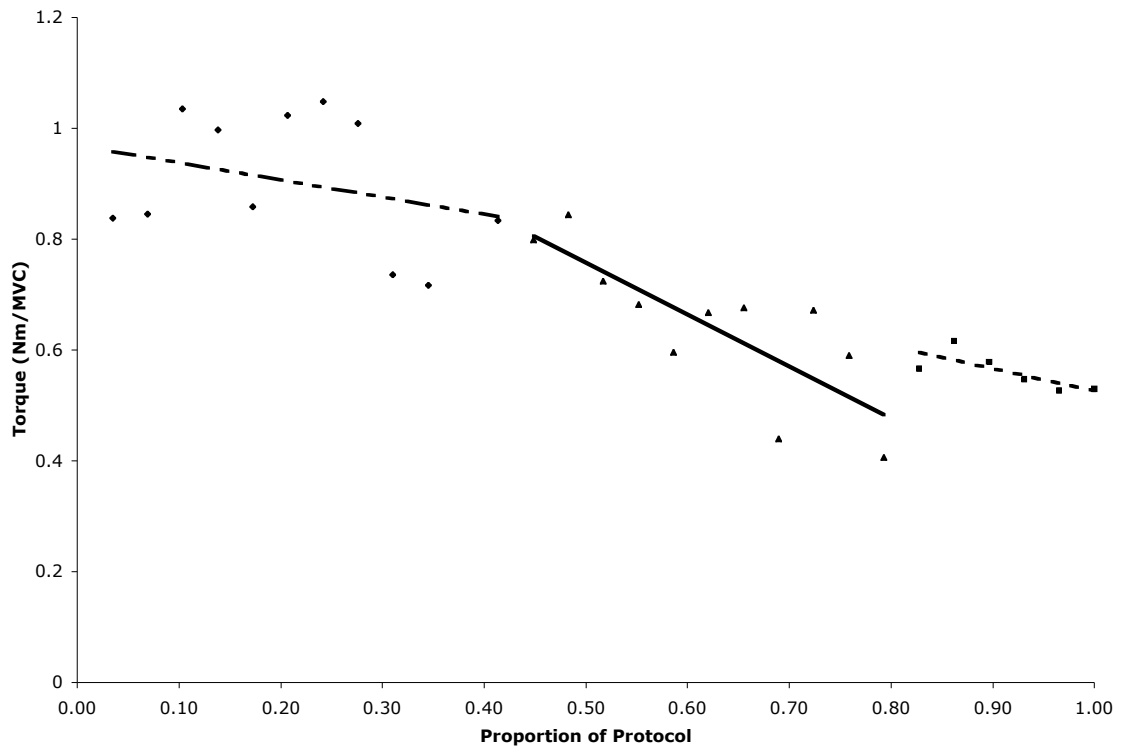


Figure 4.1: Peak concentric torque production during the fatigue protocol, broken into the three phases. The first dashed line represents the Initial phase. The solid black line represents the Decline phase and the second dashed line represents the Fatigue phase.

The sample average torque production during each phase of the fatigue protocol for both the strength and endurance-trained groups are shown in Figure 4.3.

There were no significant differences between groups regardless of training type ($p = 0.373$), nor were there significant differences for the interaction between phase and group ($p = 0.900$). There were however significant differences for torque production between all phases ($p < 0.001$) (Table 4.2).

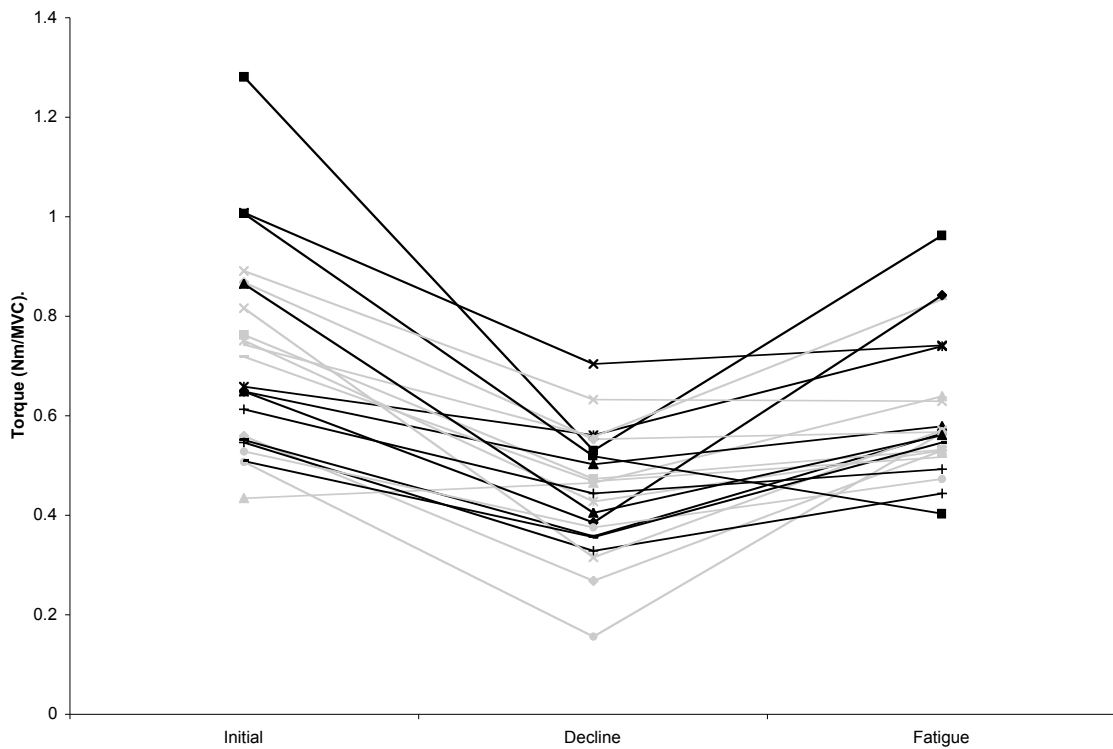


Figure 4.2: Torque production for each subject during each of the three phases ($n = 22$). Grey lines represent the strength-trained group and the black line represents the endurance-trained group.

EMG/Torque Ratio

For analysis of the EMG/Torque ratio three subjects' data were excluded from the sample. Two subjects' EMG/Torque ratios were determined to be outliers. Another subject's ratio was unavailable for processing due to failure of the EMG system during data collection. Thus, the samples analyzed were reduced to 10 subjects (9 males and 1 female) for the strength-trained group and 9 subjects (4 males and 5 females) for the endurance-trained group. The mean values of the EMG/Torque ratio during the fatigue protocol are shown for the strength-trained and endurance-trained groups in Table 4.3 and Figure 4.4.

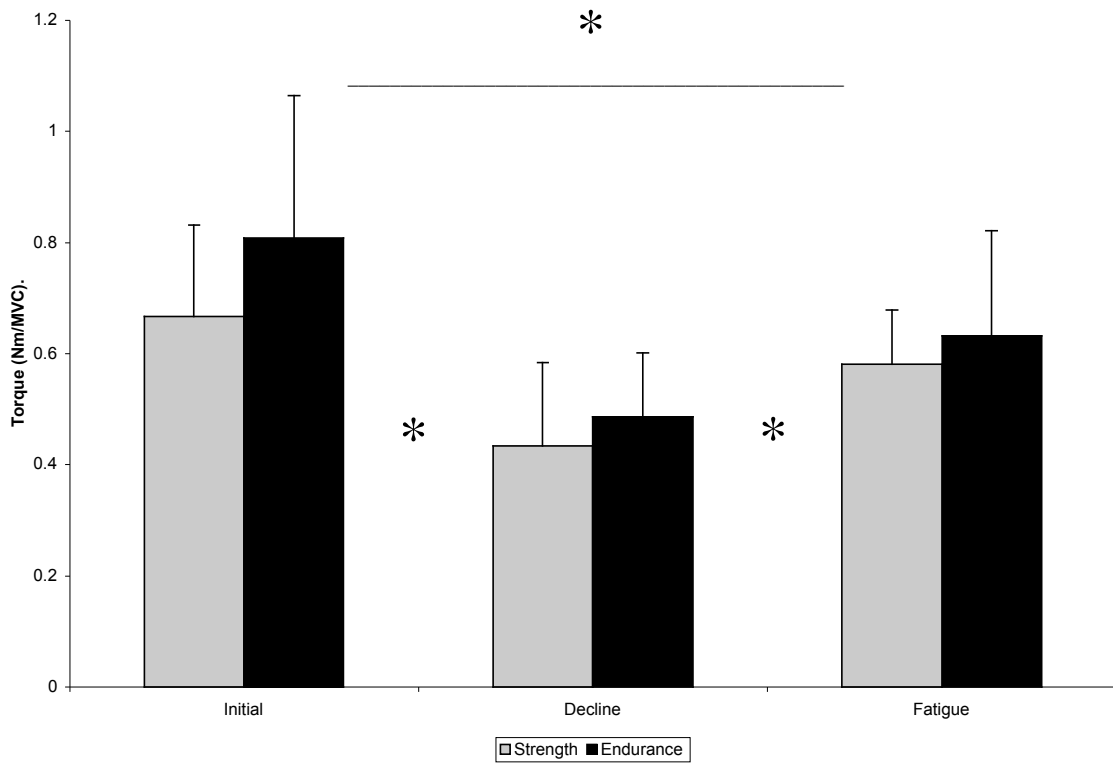


Figure 4.3: Mean torque production for both the strength-trained (n = 11) and endurance-trained (n = 11) samples during each of the three phases. (* p < 0.05)

Table 4.2: 2-Factor ANOVA with repeated measures of the fatigue protocol phases.

	df	SS	MS	F	P
Group	1	0.040	0.040	0.832	0.373
Error	20	0.969	0.048		
Phase	2	0.857	0.429	28.398	< 0.001*
Phase*Group	2	0.003	0.002	0.106	0.900
Error	40	0.604	0.015		

*significance at p < 0.05

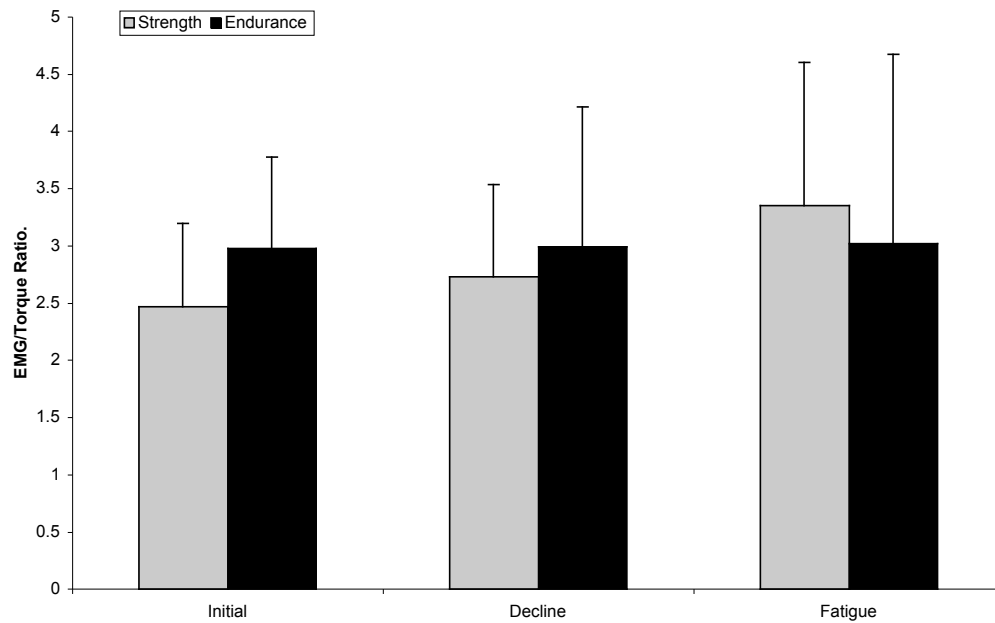


Figure 4.4: Average EMG/Torque ratio for both the strength-trained ($n = 10$) and endurance-trained ($n = 9$) samples for each of the three phases.

Table 4.3: EMG/Torque ratio during each phase: Mean (SD).

	n	Initial (V/Nm/N)	Decline (V/Nm/N)	Fatigue (V/Nm/N)
Strength	10	2.467 (0.728)	2.727 (0.809)	3.354 (1.248)
Endurance	9	2.974 (0.834)	2.995 (1.178)	3.019 (1.560)

Figure 4.4 shows a general increase of the EMG/Torque ratio with fatigue for the strength-trained group as compared to the endurance-trained group, however this difference was not significant ($p = 0.744$). There were no significant differences between the phases of the fatigue protocol ($p = 0.085$). Also, the interaction of phase and group was not significant ($p = 0.128$).

The average EMG/Torque ratio during each phase for each subject is shown in Figures 4.5a and b. The figure indicates that there were two types of EMG/Torque ratio response to acute muscular fatigue. One group ('incliners') (n = 9) appears to have increased their EMG/Torque ratio finishing in the fatigue phase with a ratio of approximately 4.0 V/Nm/N, while the second group ('decliners') (n = 10) appears to have decreased their EMG/Torque ratio, finishing with a ratio of approximately 2.0 V/Nm/N.

The average EMG/Torque ratio for the 'incliners' and 'decliners' is shown in Figure 4.6. Analysis of variance revealed significant differences between the two responses ($p < 0.001$), between phases ($p = 0.025$) and in the interaction of phase and response ($p < 0.001$) (Table 4.4).

Table 4.4: 2-Factor ANOVA table with repeated measures for the EMG/Torque ratio during each phase for the two types of responders to acute muscular fatigue.

	df	SS	MS	F	P
Response	1	25.347	25.347	19.695	< 0.001*
Error	17	21.879	1.287		
Phase	2	1.980	0.990	4.111	0.025*
Phase*Response	2	7.477	3.739	15.528	< 0.001*
Error	34	8.186	0.241		

* significance at $p < 0.05$

The mean EMG/Torque ratio for subjects by gender was 2.427 +/- 0.762 for men and 3.314 +/- 0.521 for women during the initial phase, 2.626 +/- 0.852 for men and 3.347 +/- 1.138 for women during the decline phase, and 3.096 +/- 1.225 for men and 3.412 +/- 1.766 for women during the fatigue phase of the fatigue protocol. There were

no significant differences in the EMG/Torque ratio between genders ($p = 0.171$), between the phases ($p = 0.250$), or in the interaction of the phase and gender ($p = 0.456$).

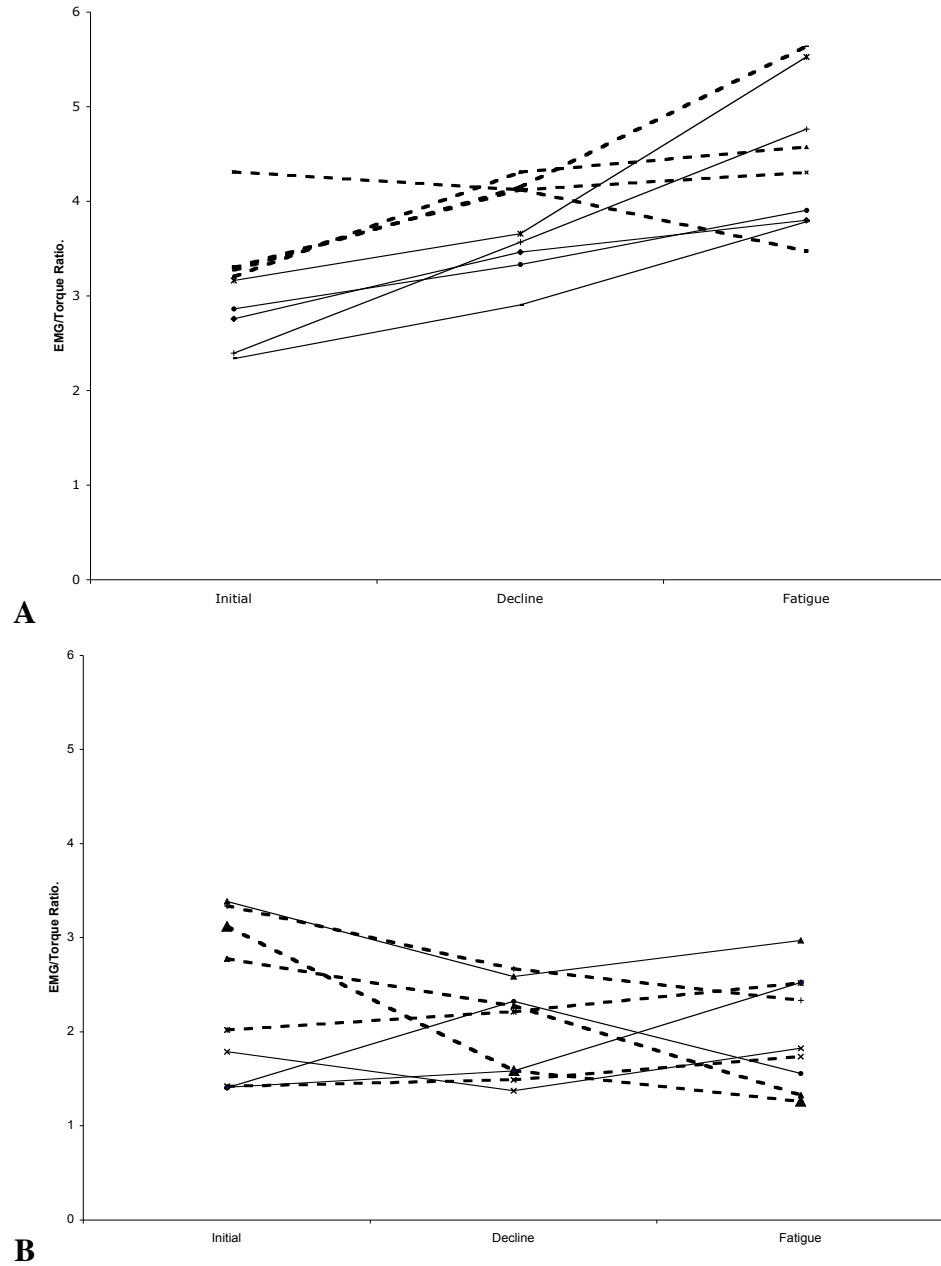


Figure 4.5a: Average EMG/Torque ratios for the ‘incliners’ ($n = 9$) during the three phases of the fatigue protocol. 4.5b: Average EMG/Torque ratios for the ‘decliners’ ($n = 10$) during the three phases of the fatigue protocol. The solid line represents the strength-trained sample, while a dashed line represents the endurance-trained group.

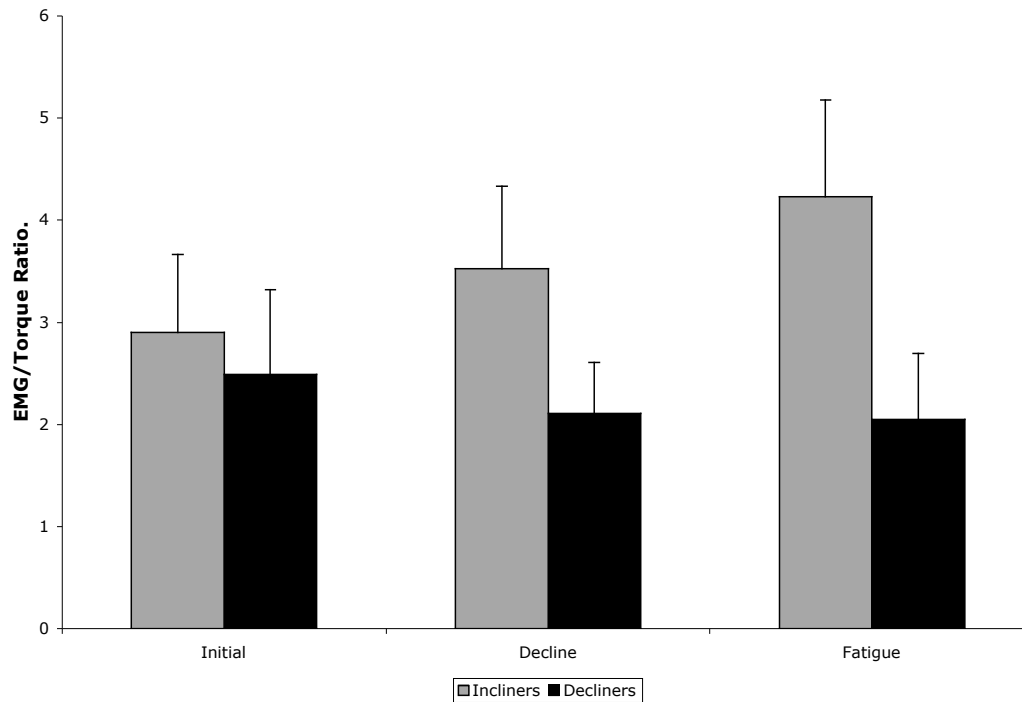


Figure 4.6: Average EMG/Torque ratio for the ‘incliners’ and ‘decliners’ during the fatigue protocol.

All female subjects were excluded from the samples and the analysis of variance was recalculated. There were not significant differences between the groups ($p = 0.964$) and for the phase*group interaction ($p = 0.935$) but there were significant differences for the phases of the fatigue protocol ($p = 0.045$) (Table 4.5).

Table 4.5: 2-Factor ANOVA table with repeated measures of phase for the EMG/Torque ratio of only the male subjects for the strength and endurance-trained samples.

	df	SS	MS	F	P
Group	1	0.005	0.005	0.002	0.964
Error	11	26.322	2.393		
Phase	2	2.376	1.188	3.570	0.045*
Phase*Group	2	0.045	0.023	0.068	0.935
Error	22	7.321	0.333		

* significance at $p < 0.05$

Functional Tests

During the functional ability tests, subjects had a non-statistically significant improvement of performance after acute fatigue. Also, the strength-trained group performed better than the endurance-trained group but did not reach statistical significance. The results for the pre-fatigue and post-fatigue single-leg hop tests are shown for both training groups in Table 4.6.

One outlier (> 3.0 IQR) was removed from the data set for the 3-forward hop test. Analysis of variance for the 3-forward hops revealed that there was a significant difference between the groups ($p < 0.001$). No significant differences existed between the pre- and post-fatigue trials ($p = 0.408$) or for the interaction between the pre- and post-fatigue trials and groups ($p = 0.140$). Figure 4.7 shows the distance covered for the strength and endurance-trained groups of the pre- and post-fatigue trials of 3-forward hop test. A repeated measures analysis of variance was also run on the differences between genders for the 3-forward hops. There were significant differences between genders ($p < 0.001$). No significant differences between the pre and post fatigue parameters (0.246) or for the interaction between the genders and pre/post fatigue ($p = 0.201$) were found. Finally, a repeated measures analysis of variance revealed significant differences between groups ($p = 0.019$) but no significant differences for pre- and post-fatigue trials ($p = 0.706$) or for the pre- and post-fatigue and group interaction ($p = 0.247$) when all female subjects were excluded from the sample set.

For the figure-8 test, there were no significant differences between groups ($p = 0.844$), between pre- and post-fatigue trials ($p = 0.286$) or for the interaction between pre- and post-fatigue and group ($p = 0.148$). Analysis for gender differences showed no

significant differences between genders ($p = 0.101$), between pre/post fatigue measures ($p = 0.273$) or between the pre/post and gender interaction ($p = 0.599$). There were no significant differences between the groups ($p = 0.853$), pre- and post-fatigue ($p = 0.330$) or for the pre- and post-fatigue and group interaction ($p = 0.152$) for a sample excluding all females. Figure 4.8 shows the average time taken to complete the figure-8 hop test for both the strength and endurance-trained groups.

Table 4.6: Pre-fatigue and post-fatigue parameters for the single-leg hop tests: Mean (SD).

		Units	N	Pre-fatigue	Post-fatigue
3-forward	Strength	m	10	6.607 (0.679)	6.575 (0.562)
	Endurance		11	5.235 (0.922)	5.345 (0.858)
Figure-8	Strength	s	11	9.417 (1.862)	9.466 (2.231)
	Endurance		11	9.464 (1.003)	9.150 (0.992)
M/L	Strength	s	11	7.464 (1.157)	7.068 (1.015)
	Endurance		10	7.811 (0.587)	7.366 (0.639)
Up/Down	Strength	s	10	15.966 (2.390)	15.566 (2.721)
	Endurance		11	17.938 (3.633)	16.459 (2.933)

One outlier (> 3.0 IQR) was removed from the data set for the M/L test. For the M/L test, there were significant differences between the pre and post-fatigue trials ($p <$

0.001). No significant differences were found between the groups ($p = 0.405$) or for the interaction of pre and post with group ($p = 0.804$). The average time (s) taken to complete the M/L hop test decreased with fatigue as shown in Figure 4.9 for both groups. The data were also processed for gender differences and results show significant differences between the genders ($p = 0.008$) and between the pre/post-fatigue measures ($p < 0.001$). Significant differences were not found for the pre/post and gender interaction ($p = 0.637$). When examined with an all male sample, there were significant differences between the groups ($p = 0.023$) but not for the pre- and post-fatigue trials ($p = 0.232$) or for the pre- and post-fatigue and group interaction ($p = 0.369$).

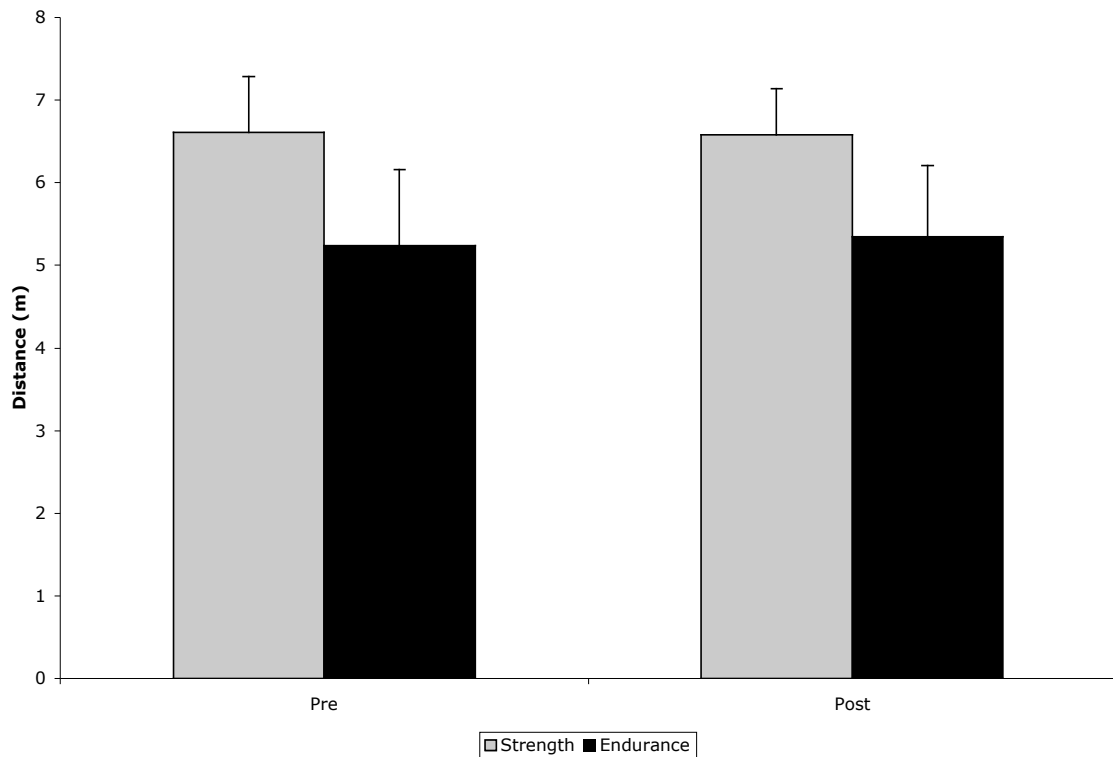


Figure 4.7: Average distance (m) for the strength-trained ($n = 9$) and endurance-trained ($n = 11$) groups for the 3-Forward hops test. Group differences were significant (<0.001).

Finally, one outlier (> 3.0 IQR) was removed from the data set for Up/Down functional ability test. For the Up/Down hops there were no significant differences between the groups ($p = 0.268$) or for interaction between pre/post and group ($p = 0.120$). There were however significant differences between the pre and post-fatigue trials ($p = 0.011$). When examined with all females subjects excluded from the sample set there were no significant differences between the groups ($p = 0.672$) or for the pre- and post-fatigue and group interaction ($p = 0.181$) but there were significant differences between the pre- and post-fatigue trials ($p = 0.001$). The average time (s) for both groups (strength and endurance) to complete the Up/Down hop test decreased with fatigue as shown in Figure 4.10.

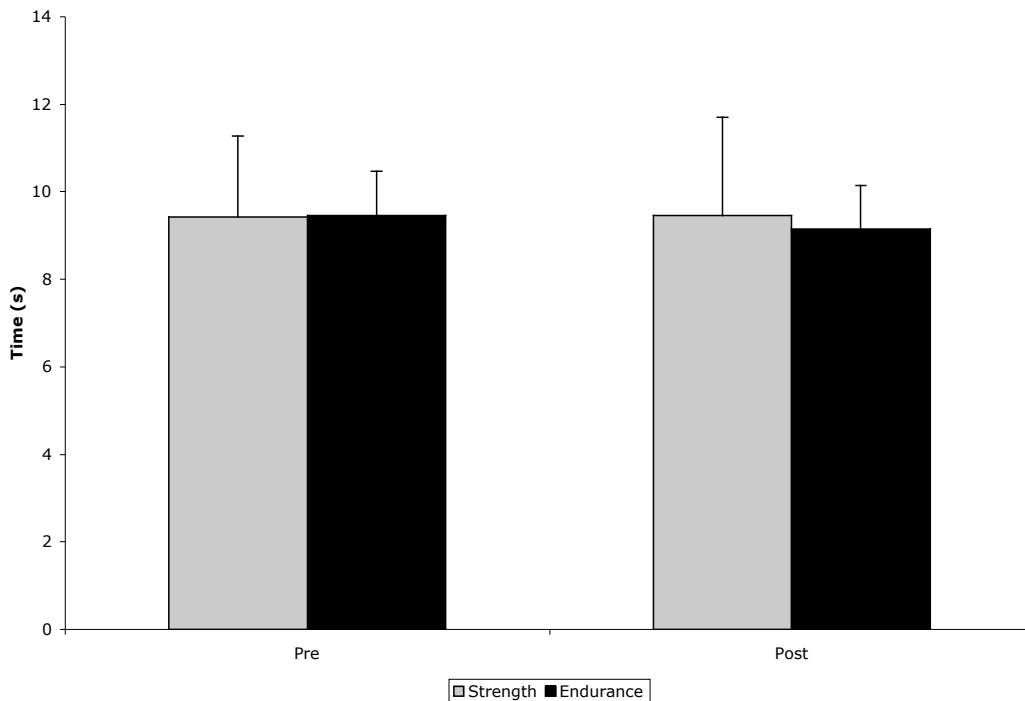


Figure 4.8: Average time (s) for the strength-trained ($n = 10$) and endurance-trained ($n = 11$) groups for the Figure-8 hop test.

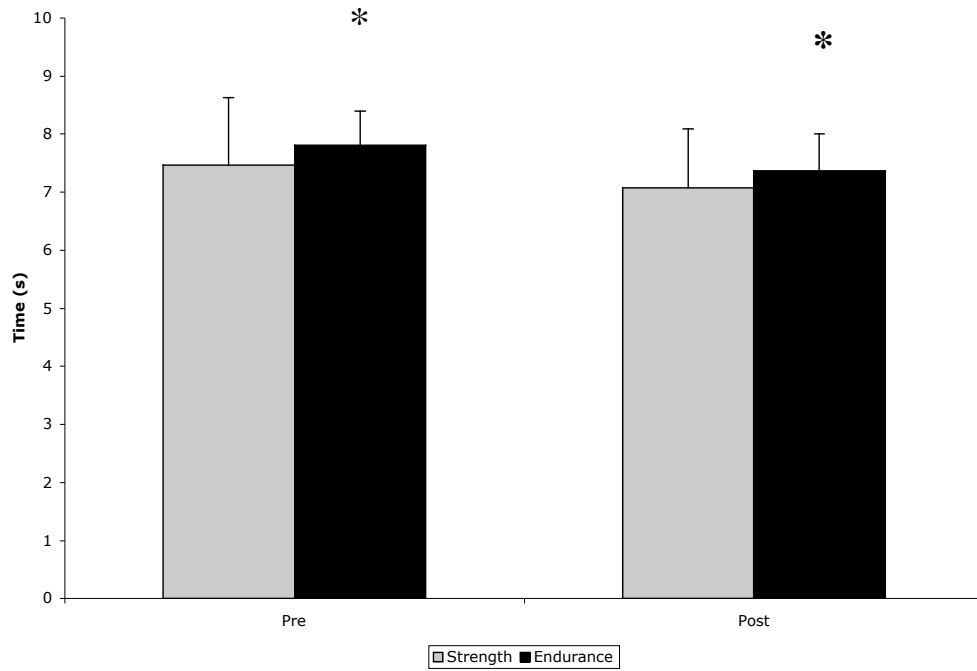


Figure 4.9: Average time (s) for the strength-trained (n = 9) and endurance-trained (n = 10) group for the M/L hop test. (* p < 0.05).

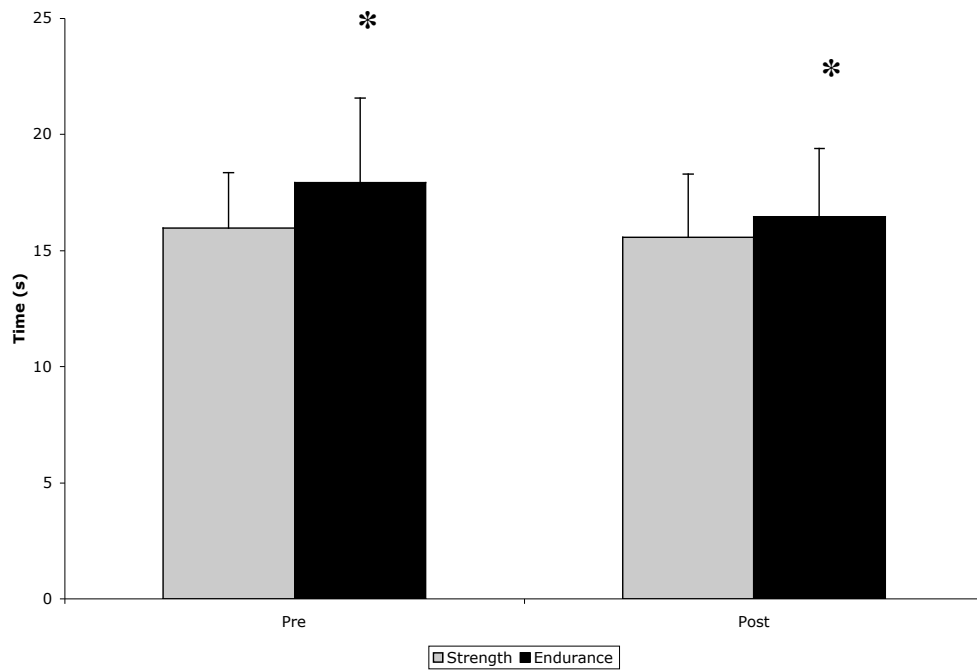


Figure 4.10: Average time (s) for the strength-trained (n = 10) and endurance-trained (n = 11) for the Up/Down hop test. (* p < 0.05)

The data were also processed for gender differences and results show significant differences between genders ($p = 0.020$) and between pre/post fatigue measures ($p = 0.011$). The pre/post fatigue and gender interaction showed no significant differences ($p = 0.598$).

CHAPTER FIVE

DISCUSSION

Introduction

The primary goal of this study was to determine the differences of the EMG/Torque ratio during acute muscular fatigue for two populations (strength and endurance). Specifically, it was hypothesized that a strength-trained sample would produce significantly greater EMG/Torque ratio than an endurance-trained sample during fatiguing isokinetic knee extension contractions. The EMG/Torque ratio was assessed by collecting EMG data from the VL of the subject's dominant leg and torque produced by the knee extensors of the same leg during fatiguing knee extensions.

The secondary goal of this study was to determine if there were significant differences between pre- and post-fatigue functional ability hopping tests and if there were significant differences between the strength-trained and endurance-trained samples for the functional ability test. To measure the functional ability of the knee joint, subjects were asked to perform four single-leg hops drills on their dominant leg pre- and post-fatigue. It was hypothesized that the parameters of the post-fatigue hopping tests would be significantly worse than the pre-fatigue hops and there would be significantly greater difference between post- and pre-fatigue hop parameters for the strength-trained sample than the endurance-trained sample.

With respect to the primary goal, there were no significant differences in the EMG/Torque ratio between the samples, but the strength-trained sample tended to produce a steeper increase of the EMG/Torque ratio during acute fatigue than the

endurance-trained sample. It is evident that there are two types of EMG/Torque ratio response to acute fatigue, but training type does not appear to play a significant role in determining the type of response of the VL to fatigue. Contrary to the secondary hypothesis, the post-fatigue functional ability tests were not significantly worse than the pre-fatigue results and contrary to the tertiary hypothesis the differences of pre- and post-fatigue functional ability test of the strength-trained sample were not significantly different from the endurance-trained.

Subject Characteristics

Twenty-two subjects (13 males and 9 females) volunteered to participate in this study from the Montana State University - Bozeman campus. Subjects were recruited for their training history (strength or endurance) and placed into two groups based on their answers to a training questionnaire (Appendix B). Subsequently, the endurance-trained group had considerably more females ($n = 7$) than did the strength-trained sample ($n = 2$). There was some difficulty in finding females who did little or no endurance training, while performing a considerable amount of strength training. The opposite trend occurred for the males. It was difficult finding males who were participating in endurance training without also performing a considerable amount of strength training. These factors contributed to the imbalance of males/female ratio in the samples, which could be a limitation of this study since it is not currently known if males and females respond similarly to acute muscular fatigue during isokinetic knee extensions. Previously, it was concluded that force production is similar between genders, but

activation magnitude is greater in females than males when fatigued for both the knee extensors and elbow flexors (Hunter et al., 2004; Lindstrom et al., 1995).

It was important for the subjects included in each sample to be purely strength or endurance trained because one purpose of this study was to compare the differences of training history on the response of the VL to acute muscular fatigue. Cross training by the subjects may dilute the findings. Large variations of training type could have been a confounding factor, as it was previously speculated that differences in EMG/Torque ratio during fatiguing contractions could be attributed to fiber type (Bigland-Ritchie, 1981). More recently, researchers concluded that fiber type does not necessarily dictate the response of the EMG/Torque ratio to fatigue (Gerdle et al., 1997). In this study, it was not feasible to measure fiber type in subjects, and therefore the samples can not be divided by fiber type. The reason for testing a purely strength-trained sample versus a purely endurance-trained sample was an attempt to control for fiber type based on fiber type differentiation from training. Thus, it was assumed that the strength-trained athletes would rely more on fast-twitch (type II) for torque production, while endurance athletes would rely more on slow-twitch (type I) fibers.

Torque Production

During the fatigue protocol, the isokinetic contractions continued until the subject reached acute fatigue. Acute fatigue was defined as when a subject had two consecutive contractions where the peak concentric torque produced was below 50% of MVC. Below 50% of MVC a subject exhibited an inability to maintain force or torque production, supporting a previous definition of muscular fatigue (Asmussen, 1979; Bigland-Ritchie,

1981; Mannion et al., 1996). Figure 4.3 shows that the mean torque produced at the end of the decline phase was at or below the specified fatigue value ($< 50\%$ MVC), demonstrating that as a group the subjects were reaching acute fatigue. However, not all subjects reached the acute fatigue value. It is possible that not all the subjects produced the specified torque declines because their protocol was either ended too early by the test administrator or they may not have given true maximum effort during the protocol.

The significant difference between peak concentric torque during the phases of the fatigue protocol was similar to previous research that reported significant declines of torque as a result of fatiguing exercise (Klass et al., 2004). There were significant differences between each phase during the fatigue protocol but there were not significant differences in the loss of torque production between the strength and endurance-trained samples. Thus, all subject's torque production responded similarly to acute muscular fatigue.

Training type does not have a significant effect on torque production during isokinetic knee extensions in response to acute muscular fatigue at $60^\circ/\text{s}$ through a functional range of motion. These results are in agreement with findings that force or torque production (normalized to body weight) are not significantly different between different populations (Hunter et al., 2004; Wretling et al., 1998). However, some interesting trends were noticed between training type samples. The endurance-trained sample was able to maintain a greater percentage of maximal torque production longer than the strength-trained sample (Figure 4.4). This could be attributed to the greater resistance of type I (slow twitch) muscular tissue to fatigue (Komi et al., 1979). In theory, the endurance-trained sample would have a greater percentage or higher reliance

on slow twitch muscle fibers giving them a lower maximal torque production but the ability to maintain torque production for a longer duration than the strength-trained sample. Torque production of the different samples was not significantly different. Thus, any differences of the EMG/Torque ratio were not a result of declines in torque production during the fatigue protocol, but can be attributed to variations in activation magnitude of the recruited muscle tissue.

EMG/Torque Ratio

Analysis of the EMG/Torque ratio revealed no significant differences between training groups or gender. However, two trends were evident from these results. The strength-trained sample tended to have a more drastic increase in their ratio during the fatigue protocol, and females tended to have a greater increase of activation magnitude than males. Also, it became evident during the analysis that there were two types of responders to acute muscular fatigue. Subjects responded to acute muscular fatigue by either increasing or decreasing their activation magnitude.

There were no significant differences of the EMG/Torque ratio between the two training groups, between the phases of the fatigue protocol or for the interaction of phase and group. But the difference of the EMG/Torque ratio between each phase ($p = 0.085$) of the fatigue protocol was near significance. It is possible that with an increased sample size significant phase differences would become evident. The lack of significant phase differences is supported in some degree by previous work which found no significant changes of EMG during fatiguing exercise (Klass et al., 2004). The present results indicate that the training type does not have a significant effect on how an individual will

respond to acute muscular fatigue. It is possible that fiber type utilized by the subjects or their level of fatigue at the beginning of the protocol could indicate how they responded. The lack of significant differences may be due to limited sample size or the large variability of the EMG/Torque ratio seen within each sample.

The results of the EMG/Torque ratio in response to acute muscular fatigue indicate two significantly different responses to muscular fatigue. All subjects began the fatigue protocol with a similar EMG/Torque ratio but as fatigue increased subjects responded in one of two fashions (“incliners” or “decliners”). The incliners increased their activation magnitude. Whether the incliners increased their activation magnitude by increased recruitment or rate coding is undetermined. Previous researchers have reached conflicting conclusions on reasons for the increased activation magnitude observed during fatiguing contractions. It has been suggested that the contraction velocity of muscle fibers does not significantly change during dynamic contractions, which would suggest that the incliners increased their activation magnitude by increasing muscle fiber recruitment (Masuda, Masuda, Sadoyama, Inaki, & S., 1999). Other researchers concluded that during maximal dynamic contractions, subjects cannot increase the number of fibers stimulated because they are already contracting “maximally” (Kay, St Clair Gibson, Mitchell, Lambert, & Noakes, 2000).

Kay et al. (2000) suggested that increased activation magnitude was a result of switching the fiber type reliance for torque production during the contraction. It is possible that the incliners relied more upon type II (fast twitch) muscle fibers during the initial phases of the fatigue protocol and that the increased VL activation signaled a switch to type I (slow twitch) fibers that have a lower fatigability. One other study has

speculated that an increase of EMG amplitude at the end of a fatiguing contraction is an indication of type I muscle fiber utilization (Perry-Rana et al., 2002).

The decliners did not increase their activation magnitude, and yet maintained torque production during the fatigue protocol. Perhaps, the decliners relied upon one type of muscle fiber to maintain torque. It is possible that the decliners began the fatigue protocol relying upon type I muscle fibers for torque production and due to the lower fatigability of type I fibers did not need to switch fiber type utilized for torque production. Another possibility for the decreased activation magnitude of the decliners could be the effects of “central” fatigue. Central fatigue inhibits performance by preventing high-force, quick fatigue type II muscle fibers from contracting (Hug et al., 2004). The decliners could have experience central fatigue during the fatigue protocol, which prevented them from recruiting the high-force type II muscle fibers. Whether an increase of fiber type recruitment, rate coding or switching of fiber type utilization, the mechanisms behind increased activation magnitude during fatigue are in need of further study.

Another possible explanation for the response of the decliners is that they could have been non-responders to the fatigue protocol. The subjects included in the decliner response may have not given a maximal effort during the fatiguing isokinetic knee extensions causing them to not maximally recruit their muscular tissue. Thus, this lack of effort could explain the decrease of the EMG/Torque ratio during the fatigue protocol. The subjects in the decliner group may also have not been properly fatigued during the protocol, which would cause them not to respond as other subjects who invoked a response to the protocol.

Another factor to consider in determining the reason for two types of EMG/Torque response to acute muscular fatigue is gender differences. Previous research found that during fatiguing contractions the amplitude of EMG is significantly different for males and females (Hunter et al., 2004; Lindstrom et al., 1995). Our results indicate no significant differences ($p = 0.171$) of the EMG/Torque ratio between genders but generally support previous findings, which found that females tended to have a higher ratio throughout (Wretling et al., 1998). Females tended to produce greater EMG/Torque ratio than males for each phase of the fatigue protocol (Table 4.8). It is possible that with additional study a gender difference could be observed for the differentiation of response to acute fatigue by the VL.

In conclusion, there were no significant differences between the strength-trained and endurance-trained samples for the EMG/Torque ratio but further examination revealed significant differences in two types of responders to acute muscular fatigue. It could be that a subject's response to acute muscular fatigue depends upon the type of muscular tissue utilized or is perhaps a result of gender differences in the activation magnitude of muscular tissue. Further research is needed to better understand these responses.

Functional Tests

During the functional ability tests two trends were observed. The strength-trained sample performed better on nearly all of the single-leg hop tests than the endurance-trained sample. Second, both groups improved their performance during the post-fatigue

trials on most of the functional ability tests. Although trends were observed in the data, there were only a couple of instances where significance was met.

During the 3-forward hop test the strength-trained sample jumped significantly further than the endurance-trained sample. It is unclear if training type was responsible for these differences. In agreement with previous research (Itoh et al., 1998), further analysis revealed significant differences between the genders for 3-forward, M/L and Up/Down hop tests. After the removal of outliers for analysis the strength-trained sample was almost entirely male for the data set of the 3-forward hops, and endurance-trained sample was primarily female. Also, the data were analyzed without females and it was found that significant group differences did exist between the training types during the 3-Forward and M/L functional ability tests. Further testing is needed before a conclusion can be drawn on whether group differences were a result of gender differences of the samples or training type differences.

There were significant differences of pre-fatigue and post-fatigue trials for two single-leg hop tests. The M/L and Up/Down hop test showed significant differences between the pre-fatigue and post-fatigue when examined by separate training groups (strength and endurance). Also, for the M/L hops there were significant differences between the pre- and post-fatigue trials when compared by gender. For both tests (M/L and Up/Down) the groups improved their times in the post-fatigue trials. Thus it was not acute muscular fatigue that accounted for the differences but perhaps improved technique. This increase in performance could be due to a learning curve for each test. Previous research has indicated that subjects will continue familiarization with functional ability tests for two to three trials (Augustsson et al., 2004). It is possible that the

subjects included in this sample were still familiarizing themselves with the single-leg hop tests after the fatigue protocol. If this was the case then the subjects' unfamiliarity with the tests could hinder their performance in the pre-fatigue tests and account for the lack of significant differences seen. Also, the subjects may not have been functionally fatigued during the protocol or could have recovered from the acute muscular fatigue because of the one-minute break between each functional ability test.

It is undetermined whether the differences seen with the functional ability test are due to training type or differences of gender. From these results we reject our secondary and tertiary hypotheses. Subjects did not perform significantly worse during the post-fatigue functional ability tests. Further, the strength-trained sample did not show greater affects of acute muscular fatigue during the functional ability tests.

CHAPTER SIX

CONCLUSION

The primary purpose of this study was to compare the differences of the EMG/Torque ratio of the knee extensors during acute muscular fatigue between two populations (strength and endurance) using surface EMG electrodes placed over the vastus lateralis of the subject's dominant leg and an isokinetic dynamometer. Subjects performed isokinetic knee extensions until reaching acute fatigue defined as below 50% of isometric maximum. The second purpose of the study was to compare the affects of acute muscular fatigue on the functional ability of the knee joint during single-leg hop tests.

Twenty-two subjects (11 strength-trained and 11 endurance-trained) completed the fatigue protocol and pre- and post-fatigue functional ability tests. There was an imbalance of the male/female ratio between the training groups, with strength-trained group being mostly male and the endurance-trained group primarily female. The gender imbalance between samples could be a limitation of the study, since the women responded differently to fatigue than males. Women tended to have a greater increase of VL activation magnitude than males.

The results indicate training type did not significantly affect torque production or the EMG/Torque ratio during isokinetic knee extensions in response to acute muscular fatigue. However, a few trends were evident. The strength-trained sample tended to have a greater increase of the EMG/Torque ratio during the fatigue protocol. The results did indicate that there were two significantly different types of response to acute

muscular fatigue. One group of responders doubled their activation magnitude during the fatigue protocol, while another group of responders did not increase their activation magnitude during the fatigue protocol. It is possible that the increase of activation magnitude seen during the fatigue protocol is a result of transition of fiber type utilization. The subjects who increased their activation magnitude may have relied upon type II muscle fibers at the beginning of the fatigue protocol and may have needed to recruit type I muscle fibers to maintain torque production.

The results of this study have limited application. The speed of contraction during the isokinetic contractions (60 °/s) was considerably slower than what would be present during athletic movements. The contraction speed had to be controlled to produce good torque decline and reliable measurement of activation magnitude of muscular tissue. If isokinetic contractions had been run at a speed mimicking athletic events there could have been problems with saturation of the EMG signal during the rapid movements. Thus, the findings are limited because they may not be applicable to acute muscular fatigue seen during many athletic events.

The results of the functional ability tests indicate that the strength-trained sample tended to perform quicker or jump farther during the functional tests than the endurance-trained sample, but the endurance-trained sample showed greater improvements from the pre- to post-fatigue trials. It is possible that the strength-trained group had more previous exposure to the single-leg hops of the functional ability test, which could account for different reactions of the two samples to acute muscular fatigue during the tests.

It is unclear whether training type or gender differences are responsible for the differences seen between the strength-trained and endurance-trained samples for the

functional ability tests. The findings of the functional ability tests may have limited application because of the gender differences of the samples and from subject unfamiliarity with the single-leg tests. It may be beneficial to provide more opportunity for the subjects to come in and familiarize themselves with the single-leg hops.

Further study is needed to determine what is the true cause of the different responses to acute muscular fatigue during fatiguing isokinetic knee extensions. It appears that training type does not indicate how a subject will respond to acute fatigue. In agreement with previous research, gender plays a significant role in response to fatigue. Thus, with further study the gender make up of the sample should be carefully controlled.

References Cited

- Alkner, B. A., Tesch, P. A., & Berg, H. E. (2000). Quadriceps EMG/force relationship in knee extension and leg press. *Medicine and Science in Sports and Exercise*, 32(2), 459-463.
- Asmussen, E. (1979). Muscle Fatigue. *Medicine and Science in Sports and Exercise*, 11(4), 313-321.
- Augustsson, J., Thomee, R., & Karlsson, J. (2004). Ability of a new hop test to determine functional deficits after anterior cruciate ligament reconstruction. *Knee Surgery Sports Traumatology Arthroscopy*, 12, 350-356.
- Babault, N., Pousson, M., Ballay, Y., & Van Hoecke, J. (2001). Activation of human quadriceps femoris during isometric, concentric and eccentric contractions. *Journal of Applied Physiology*, 91, 2628-2634.
- Babault, N., Pousson, M., Michaut, A., Ballay, Y., & Van Hoecke, J. (2002). EMG activity and voluntary activation during knee-extensor concentric torque generation. *European Journal of Applied Physiology*, 86, 541-547.
- Barber, S. D., Noyes, F. R., Mangine, R. E., McCloskey, J. W., & Hartman, W. (1990). Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Clinical Orthopedics*, 255, 204-214.
- Bigland-Ritchie, B. (1981). EMG/Force Relations and Fatigue of Human Voluntary Contractions. *Exercise and Sport Science Review*, 9, 75-117.
- Cogshall, J. C., & Bekey, G. A. (1970). Emg-Force dynamics in human skeletal muscle. *Medical and Biological Engineering*, 8, 265-270.

- Crenshaw, A. G., Gerdle, B., Heiden, M., S., K., & Friden, J. (2000). Intramuscular pressure and electromyographic responses of the vastus lateralis muscle during repeated maximal isokinetic knee extensions. *Acta Physiologica Scandinavica*, *170*, 119-126.
- Doorenbosch, C. A. M., & Harlaar, J. (2003). A clinically applicable EMG-force model to quantify active stabilization of the knee after a lesion of the anterior cruciate ligament. *Clinical Biomechanics*, *18*, 142-149.
- Eguchi, A. (2004). Effect of static stretch on fatigue of lumbar muscles induced by prolonged contraction. *Electromyogram and Clinical Neurophysiology*, *44*, 75-81.
- Fernandez, J. E., & Marley, R. J. (1998). *Applied Occupational Ergonomics: A Textbook*. Dubuque, IA: Kendall/Hunt Publishing Co.
- Gerdle, B., Karlsson, S., Crenshaw, A. G., & Friden, J. (1997). The relationship between EMG and muscle morphology throughout sustained static knee extension at two submaximal force levels. *Acta Physiol Scand*, *160*, 341-351.
- Gillard, D. M., Yakovenko, S., Cameron, T., & Prochazk, A. (2000). Isometric muscle-length tension curves do not predict angle-torque curves of human wrist in continuous active movements. *Journal of Biomechanics*, *33*(11), 1341-1348.
- Griffin, L. Y., Agel, J., Albohm MJ, Arendt EA, Dick RW, Garrett WE, et al. (2000). Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *Journal of American Academy of Orthopedic Surgery*, *8*(3), 41-50.
- Hakkinen, K., & Komi, P. V. (1983). Electromyographic changes during strength training and detraining. *Medicine and Science in Sports and Exercise*, *15*, 455-460.

- Hill, A. (1938). The heat of shortening and the dynamic constraints of muscle. *Proceedings of the Royal Society B.*, 76, 136-195.
- Hug, F., Faucher, M., Marqueste, T., Guillot, C., Kipson, N., & Jammes, Y. (2004). Electromyographic signs of neuromuscular fatigue are concomitant with further increase in ventilation during static handgrip. *Clinical Physiology and Functional Imaging*, 24, 25-32.
- Hunter, S. K., Critchlow, A., In-Sik, S., & Enoka, R. M. (2004). Fatigability of the elbow flexor muscles for a sustained submaximal contraction is similar in men and women matched for strength. *Journal of Applied Physiology*, 96, 195-202.
- Itoh, H., Ichihashi, N., & Sakamoto, T. (1989). Functional Test for the Knee Joint. *Bulletin of Allied Medical Sciences, Kobe*, 5, 75-81.
- Itoh, H., Kurosaka, M., Yoshiya, S., Ichihashi, N., & Mizuno, K. (1998). Evaluation of functional deficits determined by four different hop tests in patients with anterior cruciate ligament deficiency. *Knee Surgery Sports Traumatology Arthroscopy*, 6, 241-245.
- Kawakami, Y., Amemiya, K., Kanehisa, H., Ikegawa, S., & Fukunaga, T. (2000). Fatigue responses of human triceps surae muscles during repetitive maximal isometric contractions. *Journal of Applied Physiology*, 88, 1969-1975.
- Kawakami, Y., Kubo, K., Kanehisa, H., & Fukunaga, T. (2002). Effect of series elasticity on isokinetic torque-angle relationship in humans. *European Journal of Applied Physiology*, 87, 381-387.
- Kay, D., St Clair Gibson, A., Mitchell, M. J., Lambert, M. I., & Noakes, T. D. (2000). Different neuromuscular recruitment patterns during eccentric, concentric and

- isometric contractions. *Journal of Electromyography and Kinesology*, 10, 425-431.
- Klass, M., Guissard, N., & Duchateau, J. (2004). Limiting mechanisms of force production after repetitive dynamic contractions in human triceps surae. *Journal of Applied Physiology*, 96, 1516-1521.
- Komi, P. V., Linnamo, V., Silventoinen, P., & Sillanpaa, M. (2000). Force and EMG power spectrum during eccentric and concentric actions. *Medicine and Science in Sports and Exercise*, 32(10), 1757-1762.
- Komi, P. V., & Tesch, P. (1979). EMG Frequency Spectrum, Muscle Structure, and Fatigue During Dynamic Contractions in Man. *European Journal of Applied Physiology*, 42, 41-50.
- Larsson, B., Mansson, B., Karlberg, C., Syvertsson, P., Elert, J., & Gerdle, B. (1999). Reproducibility of surface EMG variables and peak torque during three sets of ten dynamic contractions. *Journal of Electromyography and Kinesology*, 9, 351-357.
- Lindstrom, B., Karlsson, S., & Gerdle, B. (1995). Knee extensor performance of dominant and non-dominant limb throughout repeated isokinetic contractions, with special reference to peak torque and mean frequency of the EMG. *Clinical Physiology*, 15, 275-286.
- Mannion, A. F., & Dolan, P. (1996). Relationship between myoelectric and mechanical manifestations of fatigue in the quadriceps femoris muscle group. *European Journal of Applied Physiology*, 74, 411-419.

- Masuda, K., Masuda, T., Sadoyama, T., Inaki, M., & S., K. (1999). Changes in surface EMG parameters during static and dynamic fatiguing contractions. *Journal of Electromyography and Kinesiology*, 9, 39-46.
- McHugh, M. P., Connolly, D. A. J., Eston, R. G., Gartman, E. J., & Gleim, G. W. (2001). Electromyographic analysis of repeated bouts of eccentric exercise. *Journal of Sports Sciences*, 19, 163-170.
- McHugh, M. P., Connolly, D. A. J., Eston, R. G., & Gleim, G. W. (2000). Electromyographic analysis of exercise resulting in symptoms of muscle damage. *Journal of Sports Sciences*, 18, 163-172.
- McHugh, M. P., Tyler, T. F., Greenberg, S. C., & Gleim, G. W. (2002). Differences in activation patterns between eccentric and concentric quadriceps contractions. *Journal of Sports Sciences*, 20, 83-91.
- Melhorn, J. M. (1996). A prospective study of upper extremity cumulative trauma disorders of workers in aircraft manufacturing. *Journal of Occupational and Environmental Medicine*, 38, 1264-1272.
- Metral, S., & Cassar, G. (1981). Relationship between force and integrated EMG activity during voluntary isometric anisotonic contraction. *European Journal of Applied Physiology*, 46, 185-198.
- Miyamoto, N., & Oda, S. (2003). Mechanomyographic and electromyographic responses of the triceps surae during maximal voluntary contractions. *Journal of Electromyography and Kinesiology*, 13, 451-459.

- Nordlund, M. M., Thorstensson, A., & Cresswell, A. G. (2004). Central and peripheral contributions to fatigue in relation to level of activation during repeated maximal voluntary isometric plantar flexions. *Journal of Applied Physiology*, *96*, 218-225.
- Noyes, F. R., Barber, S. D., & Mangine, R. E. (1991). Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *American Journal of Sports Medicine*, *19*(5), 513-518.
- Onishi, H., Yagi, R., Oyama, M., Akasaka, K., Momose, K., Ihashi, K., et al. (2000). Relationship between EMG signals and force in human vastus lateralis muscle using multiple bipolar wire electrodes. *Journal of Electromyography and Kinesiology*, *10*, 59-67.
- Pasacerelli, E. F. (1994). *Repetitive Strain Injury: A Computer User Guide*. New York: J. Wiley.
- Perry-Rana, S. R., Housh, T. J., Johnson, G. O., Bull, A. J., Berning, J. M., & Cramer, J. T. (2002). MMG and EMG responses during fatiguing isokinetic muscle contractions at different velocities. *Muscle Nerve*, *26*, 367-373.
- Pincivero, D. M., Coelho, A. J., Campy, R. M., Salfetnikov, Y., & Suter, E. (2003a). Knee extensor torque and quadriceps femoris EMG during perceptually-guided isometric contractions. *Journal of Electromyography and Kinesiology*, *13*, 159-167.
- Pincivero, D. M., Dixon, P. T., & Coelho, A. J. (2003b). Knee extensor torque, work and EMG during subjectively graded dynamic contractions. *Muscle Nerve*, *28*, 54-61.

- Potvin, J. R. (1997). Effects of muscle kinematics on surface EMG amplitude and frequency during fatiguing dynamic contractions. *Journal of Applied Physiology*, 82(1), 144-151.
- Rassier, D. E., MacIntosh, B. R., & Herzog, W. (1999). Length dependence of active force production in skeletal muscle. *Journal of Applied Physiology*, 86(5), 1445-1457.
- Ray, G. C., & Guha, S. K. (1983). Relationship between the surface e.m.g. and muscular force. *Medical and Biological Engineering and Computing*, 21, 579-586.
- Schillings, M. L., Hoefsloot, W., Stegeman, D. F., & Zwarts, M. J. (2003). Relative contributions of central and peripheral factors to fatigue during a maximal sustained effort. *European Journal of Applied Physiology*, 90, 562-568.
- Tate, O. J., & Damiano, D. L. (2002). Torque-EMG Relationships in Normal and Spastic Muscles. *Electromyogram and Clinical Neurophysiology*, 42, 347-357.
- Wickiewicz, T. L., Roy, R. R., Powell, P. L., Perrine, J. J., & Edgerton, V. R. (1984). Muscle Architecture and Force Velocity Relationships in Humans. *Journal of Applied Physiology*, 57, 435-443.
- Wretling, M. L., & Henriksson-Larsen, K. (1998). Mechanical Output and Electromyographic Parameters in Males and Females During Fatiguing Knee-Extensions. *International Journal of Sports Medicine*, 19, 401-407.

APPENDICES

APPENDIX A

SUBJECT CONSENT FORM

**SUBJECT CONSENT FORM
FOR PARTICIPATION IN HUMAN RESEARCH
MONTANA STATE UNIVERSITY**

PROJECT TITLE: THE EFFECTS OF ACUTE MUSCULAR FATIGUE ON THE FUNCTIONAL PERFORMANCE OF THE KNEE JOINT

PROJECT DIRECTOR: Tyler N. Brown, Graduate Student, Biomechanics
Dept. of Health and Human Development
Movement Science / Human Performance Laboratory
Montana State University, Bozeman, MT 59717-3540
Phone: (406) 994-6325; Fax: (406) 994-6314
E-mail: tnbrown@montana.edu

FUNDING: This project is not currently funded.

PURPOSE OF THE STUDY:

The purpose of this study is to assess the effects of acute muscular fatigue on the functional ability of the knee joint. Additionally, the electrical activity of the knee extensors will be measured. Involvement in this project includes a single visit to the Movement Science / Human Performance Laboratory (basement of Romney Building, MSU campus) lasting approximately 70 minutes. There are two major sections to the laboratory experiments:

- Measurement of joint torque production using a computerized dynamometry system.
- Analysis of movement for single-leg hopping.

STUDY PROCEDURES:

After reading and signing the Informed Consent Document, you will be asked to change into athletic shorts, tank top shirt, socks and athletic shoes.

Next, you will be asked to perform a battery of single-leg hop tests, to test pre-fatigue functional ability of the knee joint. Two trials of four single-leg hop tests will be performed including: three hop for distance, figure-eight hop, medial/lateral hop and up/down hop. You will be asked to hop on your dominant leg. After completion of the pre-fatigue functional ability test, you will be given the option to continue warming up by either riding a cycle ergometer or walking on a treadmill, while the principal investigator readies the equipment.

After warming up, surface electrodes will be placed on one of the quadriceps muscles of your dominant leg to measure electrical signals of muscle activation. The skin overlying the muscle will be site-prepared by cleaning with rubbing alcohol to remove any dirt or

oils. To minimize any discomfort you will be asked to perform the site-preparation. Electrode placement over the vastus lateralis will be over the lower third of the anterior surface of the thigh.

Following electrode placement, maximal joint strength will be assessed. You will be asked to push against a padded bar with your lower leg. Part of assessing your joint strength will require you to perform contractions until you have reached muscular fatigue. You may experience minor muscular discomfort during the fatigue protocol. The muscular discomfort experienced will be similar to that felt after weight lifting or running a long sprint. After completion of joint strength assessment, you will be asked to repeat the battery of single-leg hop tests performed earlier.

The entire testing session will take less than 70 minutes to complete. You will be allowed periods of rest throughout the testing procedures, and water will be provided.

POTENTIAL RISKS:

It is possible that you will feel minor muscular discomfort and fatigue during and following the experiments. You may feel free to stop the test at any time. The risk is minimal, and is expected to be less than that experienced during a moderate-intensity aerobic fitness session. The Project Director and research staff have received training in the procedures and will take the utmost precautions to assure your privacy and comfort.

BENEFITS:

Although you personally will not receive any physical benefits from this research, the results of this study may contribute to more effective musculoskeletal therapies leading to improved rehabilitation programs being designed and implemented in the field of physical medicine. All participants will receive informal feedback regarding the functional ability of the knee joint. The information may be useful to individuals involved in sporting activities or physical rehabilitation. Additionally, study participants may request a summary of the study findings by contacting the Project Director, Tyler Brown, by phone (406-994-6325) or by E-mail (tnbrown@montana.edu).

CONFIDENTIALITY:

Personal information, and all recorded data will be regarded as privileged and confidential materials. Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. Subject identities will be kept confidential by coding the data using subject pseudonyms. The code list will be kept separate and secure from the actual data files.

FREEDOM OF CONSENT:

Participation in this project is completely voluntary.

You may withdraw consent for participation in writing, by telephone, or in person without prejudice or loss of benefits (as described above). Please contact the Project

Director, Tyler Brown, by phone (406-994-6325) or by E-mail (tnbrown@montana.edu) to discontinue participation.

In the UNLIKELY event that your participation in the project results in physical injury to you, the Project Director will advise and assist the participant in receiving medical treatment. Montana State University cannot be held responsible for injury, accidents, or expenses that may occur as a result of your participation in this project. Additionally, Montana State University cannot be held responsible for injury, accidents, or expenses that may occur as a result of traveling to and from your appointment at the Movement Science / Human Performance Laboratory. *Further information regarding medical treatment may be obtained by calling the Project Director, Tyler Brown, at 406-994-6325.* You are encouraged to express any questions, doubts or concerns regarding this project. The Project Director will attempt to answer all questions to the best of their ability prior to testing. The Project Director fully intends to conduct the study with your best interest, safety and comfort in mind. *Additional questions about the rights of human subjects can be answered by the Chairman of the Human Subjects Committee, Mark Quinn, at 406-994-5721.*

PROJECT TITLE:

THE EFFECTS OF ACUTE MUSCULAR FATIGUE ON THE FUNCTIONAL PERFORMANCE OF THE KNEE JOINT

STATEMENT OF AUTHORIZATION

I, *the participant*, have read the Informed Consent Document and understand the discomforts, inconvenience, risks, and benefits of this project. I, _____ (*print your name*), agree to participate in the project described in the preceding pages. I understand that I may later refuse to participate, and that I may withdraw from the study at any time. I have received a copy of this consent form for my own records.

Signed: _____ **Age** _____ **Date** _____

APPENDIX B

SUBJECT ACTIVITY QUESTIONNAIRE

SUBJECT ACTIVITY QUESTIONNAIRE

Subject # _____ Date _____

Have you been training regularly for 2 years or more? Yes No

Is the majority of your training: Strength Endurance

Strength

Do you measure your strength gains? (eg. 1 RM) Yes No

Do you do any cardiovascular training? Yes No

Do you measure your endurance performance?
(eg. Timed mile) Yes No**Endurance**Do you measure your endurance performance?
(eg. Timed mile) Yes No

Do you do any strength training? Yes No

Do you measure your strength gains? (eg. 1 RM) Yes No