Neuromuscular consequences following anterior cruciate ligament reconstruction

Amy E. Clements

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entitled

Neuromuscular Consequences Following Anterior Cruciate Ligament Reconstruction

By

Amy E Clements, ATC

Submitted to the Graduate Faculty as partial fulfillment of the requirements for

The Master of Science Degree in

Exercise Science

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The University of Toledo

May 2013
An Abstract of
Neuromuscular Consequences Following Anterior Cruciate Ligament Reconstruction
by
Amy E Clements, ATC

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Objective: Determine if anterior cruciate ligament reconstructed (ACLr) participants present with alterations in corticomotor excitability, spinal-reflexive excitability, and voluntary activation in the quadriceps of their injured limb compared to their uninjured limb as well as matched limbs of healthy matched controls. It was also of interest to examine the relationship between inter-limb differences in corticomotor excitability, spinal-reflexive excitability, and voluntary quadriceps activation in an ACLr population. Design and Setting: A case-control study. All data were collected in a controlled research laboratory during a single testing session. Subjects: Fifty-three participants were tested and placed in two groups based on injury history, an ACLr (9 male/18 female; 20.81 ± 1.86 years; 170.92 ± 10.39 cm; 72.39 ± 14.45 kg) and healthy control group (9 male/17 female; 21.19 ±4.92 years; 171.55 ± 8.72 cm; 72.24 ± 16.92 kg). Measurements: Corticomotor excitability of the quadriceps was quantified using active motor thresholds (AMT) elicited via transcranial magnetic stimulation (TMS). AMT was defined as the lowest TMS intensity required to elicit 5 motor evoked potentials (MEP) of > 100 µV, with 6 negative MEPs of < 100µV recorded at the output 1% less. AMT was measured during a standardized quadriceps contraction of 5%
maximal voluntary isometric contraction (MVIC). Maximal Hoffmann reflexes (H-reflex) normalized to maximal muscle responses (H:M) were used to assess quadriceps spinal-reflexive excitability. Electrical stimulus was applied to the femoral nerve and was increased in 0.2volt increments until a maximum H-reflex was elicited. The stimulus was then increased until a maximal muscle response was elicited. The average of three maximal H-reflexes were normalized to the average of the three muscle responses to create our H:M outcome variable. Quadriceps activation was evaluated using the central activation ratio (CAR) via means of the burst superimposition technique. Participants performed three MVICs, with a supramaximal automated stimulus triggered once the participant reached a maximal plateau in torque. CAR was calculated as a ratio comparing the participant’s maximal voluntary torque output to the maximal torque produced with the supramaximal stimulus. Inter-limb difference scores (injured – uninjured) were calculated for each variable for further analysis. Results: A significant interaction effect was found for AMT (p = 0.027). Post hoc analysis revealed that the injured limb of the ACLr group demonstrated higher AMT values than the uninjured limb of the ACLr group (p=0.019). No other differences in AMT were detected. No significant differences were found between group or limb for H:M (p = 0.628) or CAR (p = 0.285). There was a significant, negative moderate relationship between H:M and CAR inter-limb difference scores (ρ = -0.436, p = 0.026). No significant relationship was found between H:M and AMT inter-limb difference scores (ρ = -0.158, p = 0.441) or between AMT and CAR inter-limb difference scores (ρ = -0.036, p = 0.862). Conclusion: Active motor thresholds were shown to be higher in the injured limb of the ACLr population compared to the uninjured limb, demonstrating deficits in corticomotor excitability.
within an ACLr population. We also found a relationship between spinal-reflexive excitability and voluntary activation inter-limb difference scores of an ACLr population, potentially revealing an up-regulation of neural pathways post injury. More research is needed to examine how neural alterations progress during ACL injury, and to determine the extent to which neural alterations affect function post ACL reconstruction.
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Table of Contents

Abstract........................................................................................................................................... iii

Acknowledgements...................................................................................................................... vi

Table of Contents ........................................................................................................................ vii

List of Tables ................................................................................................................................... x

List of Abbreviations .................................................................................................................... xi

1 Introduction .................................................................................................................................. 1
   1.1 Statement of the Problem ...................................................................................................... 2
   1.2 Statement of the Purpose ...................................................................................................... 3
   1.3 Significance of the Study ...................................................................................................... 3
   1.4 Research Hypothesis ............................................................................................................. 4

2 Literature Review ....................................................................................................................... 6
   2.1 Introduction .......................................................................................................................... 6
   2.2 Quadriceps Muscle Strength and Voluntary Activation .................................................... 7
   2.3 Spinal-reflexive Excitability ............................................................................................... 10
   2.4 Corticomotor Excitability ................................................................................................... 12

3 Methods ..................................................................................................................................... 15
   3.1 Study Design ......................................................................................................................... 15
   3.2 Instrumentation ...................................................................................................................... 16
3.2.1 Spinal-reflex Excitability ..............................................................16
3.2.2 Corticomotor Excitability ..............................................................17
3.2.3 Quadriceps Voluntary Activation ....................................................18
3.3 Procedure ..........................................................................................18
  3.3.1 Participant Preparation .................................................................18
  3.3.2 Maximal Voluntary Isometric Contraction (MVIC) .........................18
  3.3.3 Corticomotor Excitability ..............................................................19
  3.3.4 Spinal-reflexive Excitability ..........................................................20
  3.3.5 Measurement of Quadriceps Voluntary Activation (CAR) ...............22
  3.3.6 Statistical Analysis .......................................................................23

4 Results ..................................................................................................24
  4.1 Participants .......................................................................................24
  4.2 Group by Leg Differences ..................................................................24
  4.3 Relationship Between Inter-limb Difference Scores ...............................25

5 Discussion ............................................................................................27
  5.1 Differences in Corticomotor Excitability Between ACLr Limbs ..........27
  5.2 No Deficits Observed in Voluntary Activation ....................................29
  5.3 No Deficits Observed in Spinal-reflexive Excitability ..........................31
  5.4 Relationship of Spinal-reflexive Excitability, Corticomotor Excitability and Voluntary Activation Inter-limb Differences Scores in ACLr Population ..........32
  5.5 Limitations .......................................................................................33
  5.6 Future Research ................................................................................34
  5.7 Conclusion .......................................................................................35
References...................................................................................................................................................37

Appendix

A. Informed Consent for Human Research Study ..................................................44

B. TMS Exclusion Criteria Form ........................................................................53

C. Knee Injury History Form .............................................................................54

D. International Knee Documentation Committee Form ..................................56

E. Lower Extremity Functional Scale .................................................................59

F. Tegner Activity Level Scale ........................................................................61
List of Tables

4.1 Subject Demographics ...........................................................................................................25
4.2 AMT, H:M and CAR ANOVA Results ....................................................................................26
List of Abbreviations

ACL…………….Anterior cruciate ligament
ACLd………….Anterior cruciate ligament deficient
ACLR………….Anterior cruciate ligament reconstruction
AMI………….Arthrogenic muscle inhibition
AMT………….Active Motor Threshold

CAR………….Central activation ratio
CNS………….Central nervous system

EMG………….Electromyography

ITT………….Interpolated twitch technique

H-reflex…….Hoffmann Reflex
H:M………….Maximal Hoffmann-reflex to maximal muscle response ratio

M-response…..Maximal muscle response
∝MN………….Alpha motor neuron
MN-pool……..Motor neuron pool
MVIC…………Maximal voluntary isometric contraction

OA…………….Osteoarthritis

TMS………….Transcranial magnetic stimulation

SIB………….Superimposed burst technique

QA………….Quadriceps Activation
Chapter 1

Introduction

Anterior cruciate ligament (ACL) rupture is one of the most common injuries associated with physical activity, with an estimated 250,000 ACL ruptures occurring annually in the United States.\(^1\) The total costs associated with ACL reconstruction (ACLr) and rehabilitation is approximately 17,000 USD per patient\(^1\), reaching approximately 3 billion USD annually.\(^1\) Anterior cruciate ligament reconstruction is performed to increase joint stability; unfortunately, it is well known that ACLr is associated with an eight to ten fold increase in risk of developing knee osteoarthritis (OA).\(^2\) Patients with ACLr have demonstrated radiographic arthritic joint changes appearing as soon as 12 years post-surgery with an average time from ACLr to total knee replacement being 19 years,\(^3\) which places further economical stress on the healthcare system.

Increased disability and the risk of chronic disease may be linked to continual muscle weakness that persists long after the completion of traditional therapeutic rehabilitation.\(^4\) This muscle weakness ultimately leads to altered functional movement patterns that reduce proper muscle force attenuation during gait and jump landing tasks in people with ACLr.\(^5\) It is known that neural inhibition of key muscle groups, such as the
quadriceps, is noticeably affected following ACLr, and can be linked to continuation of these inefficient and potentially unsafe movement patterns. However, it is unclear which of the neural pathways are contributing significantly to this harmful neuromuscular response following ACL injury and reconstruction.

Traditional rehabilitation, which focuses on restoring function by focusing on flexibility and increasing muscle strength through resistance training, has only shown moderate improvements in physical function and has not addressed persistent quadriceps weakness nor diminished the incidence of knee OA following injury. Unfortunately, traditional rehabilitation does not target neural deficits that may be present following ACLr. Because of the unsatisfactory long term outcomes associated with conventional rehabilitation, some have suggested that targeting the deficits in neural mechanisms may be needed to regain full neuromuscular function and force generating capabilities of the quadriceps muscles. Prior to targeting these neural mechanisms, we must first establish how these neural pathways are affected following ACLr.

1.1 Statement of the Problem

Neuromuscular deficits following joint injury are common and persistent, specifically in the quadriceps following ACL injury. Decreases in quadriceps volitional activation and strength have been shown to alter lower extremity joint kinematics, leading to increased loading at the knee joint and negatively affect self-reported measures of disability. These dysfunctions are hypothesized to link ACLr to the development of tibiofemoral osteoarthritis (OA). Recent research has suggested that the beginning of neuromuscular deficits occur through neural adaptations of key musculature, yet the mechanisms of neural inhibition still remains unclear.
Understanding how neural pathways are affected following ACLr, compared to a healthy population, may aid in the identification of the cause of neuromuscular deficiencies; eventually leading to new approaches in targeting these neural inhibitory mechanisms and decreasing the amount of dysfunction in patients after ACL injuries.

1.2 Statement of the Purpose

It is the purpose of this investigation to determine if:

**Aim 1:** Participants with ACLr present with alterations in corticomotor excitability, spinal-reflexive excitability, and voluntary activation in the quadriceps of their involved limb compared to their uninvolved limb and healthy matched controls.

**Aim 2:** There is a relationship between inter-limb differences in corticomotor excitability, spinal-reflexive excitability, and voluntary activation in an ACLr population.

1.3 Significance of the Study

Anterior cruciate ligament injuries are significant because they occur often in the physically active. Each year, an estimated 80,000 to more than 250,000 ACL injuries occur in many young athletes 15 to 25 years of age.\(^1\) This group comprises more than 50% of those with ACL injuries, and in 2004 was ranked sixth among the most common surgical procedures by all sports medicine fellows.\(^1\) Injuries to the ACL result in overall higher costs on the medical system, and place further financial stress on the health care system due to a higher risk of developing inactivity related co-morbidities, such as obesity, diabetes, and cardiovascular disease, in association with the previous injury.\(^15\) The associated co-morbidities have been reported to arise in ACLr individuals due to alterations in neuromuscular control, which may lead to progression of osteoarthritis (OA) and an inability to participate in physical activity.\(^2\) The development of OA may
elicit knee pain and functional limitations, resulting in lifestyle modifications as a result of a previous ACL injury. It is thought that the risk of OA following ACLr is increased due to abnormal knee alignment during functional tasks due to neuromuscular dysfunction. Neuromuscular deficits following joint injury are common and enduring, specifically in the quadriceps following ACLr. Decreases in quadriceps volitional activation and strength have been shown to alter lower extremity kinematics, leading to increased loading at the knee joint. These deficits, which are defined as the inability to volitionally contract the musculature surrounding the joint, are hypothesized to link the ACLr population to the development of knee osteoarthritis.

The specific origin of these neuromuscular alterations are not well understood, but are hypothesized to generate from a neural level, specifically through corticomotor and spinal-reflexive pathways. It is important to understand how these pathways interact in this population to help develop interventions to target these pathways.

1.4 Research Hypothesis

**Aim 1:** We hypothesize that ACLr individuals will experience altered levels of neural excitability and voluntary activation in the quadriceps muscle, compared to their contralateral healthy limb, as well as healthy matched controls. Neural excitability will be assessed through both spinal-reflexive and corticomotor pathways. Spinal-reflexive excitability will be evaluated by using the Hoffmann-reflex to maximal muscle response ratio (H:M). Corticomotor excitability will be assessed through means of active motor threshold (AMT) elicited using transcranial magnetic stimulation (TMS). We hypothesize that these neural pathways will help to understand deficits seen in voluntary quadriceps
muscle activation following ACLr. Voluntary quadriceps activation will be assessed via the central activation ratio (CAR).

**Aim2:** We hypothesize there will be strong positive correlations among the inter-limb differences in corticomotor excitability, spinal-reflexive excitability and voluntary activation of the quadriceps in the ACLr group. Specifically, we expect a significant negative relationship when assessing corticomotor excitability by means of AMT, as a higher AMT signifies a decrease in corticomotor excitability.
Chapter 2

Literature Review

2.1 Introduction

Investigating the neuromuscular effects of anterior cruciate ligament (ACL) injuries is important because approximately 250,000 ACL ruptures occur in the United States each year,\(^1\) at roughly $17,000 per reconstructive surgery the total annual cost is approximately three billion dollars.\(^1\) ACL reconstruction (ACLr) is performed to increase joint stability, but unfortunately it is well known that the ACLr population eight to ten times more likely to develop knee osteoarthritis (OA) at an early age.\(^12\) ACLr patients have seen radiographic arthritic joint changes appearing as soon as 12 years post-surgery and an average time from ACLr to total knee replacement being 19 years,\(^3\) which places further stress on the healthcare system.

The risk of chronic disease and an increase in disability may be linked to persistent muscle weakness and muscle activation deficits that remain long after the completion of traditional rehabilitation. The overall decrease in muscle strength ultimately leads to altered functional movement patterns in the ACLr population and cause a reduction in muscle force attenuation during gait and activities of daily living.\(^5\) It is known that neural inhibition of key muscle groups, such as the quadriceps, is drastically affected following
ACLr, and can be linked to continuation of these inefficient and potentially unsafe movement patterns.\textsuperscript{6} It is currently unclear how the neural pathways are significantly contributing to this harmful neuromuscular response following ACL injury and reconstruction. Understanding the origins of this neuromuscular dysfunction, and how these neural pathways are affected, could potentially lead to optimal interventions, treating the origins of these unfortunate outcomes following ACL injury.

2.2 Quadriceps Muscle Strength and Voluntary Activation

Quadriceps weakness persists following knee joint injury, specifically ACLr, and has been frequently reported in the literature.\textsuperscript{5,10} Strength and muscle endurance of the quadriceps muscle group is vital for normal knee joint function;\textsuperscript{5} therefore, restoring normal quadriceps muscle function after knee injury is an essential component of therapeutic rehabilitation. Diminished muscle strength, particularly in the quadriceps muscle group, is a persistent consequence following ACL injury and reconstruction. Injury to the ACL causes deformation of the joint mechanoreceptors, which then relays altered afferent signal to the central nervous system (CNS).

An important underlying factor contributing the persistent quadriceps weakness following injury is arthrogenic muscle inhibition (AMI), which remains understudied in current clinical research in patients with knee joint injury.\textsuperscript{15} AMI is an ongoing, reflexive response following joint injury and describes the inability to completely contract a muscle even though there is no structural damage to the muscle or innervating nerve.\textsuperscript{5} This is a result of a damaged or altered signal being sent from Ruffini fibers, Pacinian corpuscles or Golgi Tendon Organs after musculoskeletal injury. The term AMI is described as a reflexive response to joint injury because it is embedded in the reflexive
loop of the neural system, and is beyond conscious, voluntary control. However, this reflexive response to injury prevents full activation of the motor neuron, resulting in decreased levels of voluntary activation. This is important for athletic trainers and other allied health care professionals to understand because AMI is often manifested as posttraumatic weakness and muscle atrophy that may persist long after the original injury. The inability to functionally activate the quadriceps after knee injury, specifically ACL, may be a cause of persistent weakness, and result in kinematic and kinetic changes during gait; this may compromise the ability of the lower extremity muscles to appropriately respond to joint loading and activities of daily living. It is important for clinicians to understand the prevalence and clinical effects of AMI in order to develop strategies to overcome this impairment.

Condensing published findings regarding AMI after knee joint injury is difficult given the variety of measurement techniques and formulas used to calculate quadriceps AMI. Force-based measures of quadriceps activation have been used to determine the proportion of the quadriceps motor neuron pool that can be volitionally activated. Techniques used to measure force-based muscle activation include the superimposed burst technique (SIB) and interpolated twitch technique (ITT). These techniques use a supramaximal, percutaneous electric stimulation during a maximal, voluntary isometric knee extension contraction to calculate the central activation ratio (CAR). CAR is a ratio comparing the participant’s maximal voluntary torque output to the maximal torque produced with an external stimulus (Figure 2.1).
Figure 2.1: Central Activation Ratio (CAR) Calculation. “A” Represents the maximal voluntary quadriceps contraction, while “B” Represents the maximal voluntary quadriceps contraction plus the additional force caused by the superimposed burst. CAR = (A/ B) * 100

In theory, when using SIB or ITT, if an individual is able to fully contract all motor units in the quadriceps, the electrical stimulation will not cause a force-producing contraction that is greater than the volitional contraction. People who are able to voluntarily contract their quadriceps at 95% or higher of their maximal contraction capability are considered to be fully activated.

Acknowledging AMI and understanding its potential effects on long-term joint health in the injured knee are vital in order to restore full mechanical function clinically. AMI has been hypothesized to contribute to the significant isokinetic quadriceps strength deficits that have been reported following ACL injury (10-38% compared to uninjured limb), and possibly influences the persistent nature of these deficits, lasting between 5 and 15 years following ACLr, even after full therapeutic rehabilitation has finished. The same researchers hypothesize that the decreased ability to produce quadriceps torque is a physiological protective mechanism used to decrease anterior shear force on the knee. Additionally, through loss of voluntary activation and strength, AMI is thought to result in significant atrophy after ACL injury. Past research has focused mainly on patients with ACL deficiency (ACLd) and showed that ACLd patients had an average of 81.47%
quadriceps activation when compared to the contralateral uninjured limb being at 86.78%. This data shows the difference in quadriceps muscle function in ACLd patients compared to knees with healthy, intact ACLs. It is important to note however, that these individuals are also showing less than optimal voluntary activation on their uninvolved limb, leading researches to believe that these effects may be bilateral in nature. It is extremely important to understand the functional deficits that may arise due to the change in muscle activation following ACL injury. Exploring the root of these deficiencies has led researchers to investigate neural pathways, such as corticomotor and spinal-reflexive, to see how they may contribute to muscle strength and activation deficits in patients after ACL injury.

2.3 Spinal-reflexive Excitability

Originally described by Paul Hoffmann in 1910, the Hoffmann Reflex (H-reflex) is an electrically induced reflex equivalent to the mechanically induced spinal stretch reflex. The Hoffmann reflex is an estimate of motor neuron pool (MN-pool) recruitment. Electrical stimulation of a mixed nerve evokes two distinct EMG responses from the affected muscle. One response to the stimulus is an action potential with a latency response between 19 and 40 milliseconds, depending on the muscle. This latent period is a result of the primary afferent stimulation, which in turn excites alpha motor neurons (αMN) in the anterior horn of the spinal cord: this response is the H-reflex. As the intensity of the stimulus increased, more afferent fibers are stimulated, therefore causing more MNs to be recruited within the MN pool. This is represented as an increase in electromyographic (EMG) amplitude of the twitch of the affected muscle as measured by a surface electrode. As the external stimulus intensity is progressively increased, a
second response appears between 5 and 15 milliseconds. This response is a direct stimulation of efferent $\alpha$MN fibers, and it is termed the maximal muscle response (M-response). When an efferent motor fiber reaches threshold, an action potential travels to the muscle and also back to the cell bodies in the anterior horn of the spinal cord, causing an observable muscle twitch, and the H-reflex to appear. The altered afferent signal results in an inhibition of the motor neuron, shutting down the quadriceps muscle group as a protective mechanism. An altered afferent signal travels to the spinal cord, synapses at the spinal cord and interneuron, and then synapses on the alpha motor neuron. The altered signal to the alpha motor neuron triggers a protective response and results in a decrease in quadriceps activation and muscle function. This decrease in muscle activation can reflect the H-reflex amplitude and has been shown to decrease after injury, representing inhibition of an uninjured muscle around an injured joint. The H-reflex is a very valuable measurement technique for researchers and clinicians in the orthopedic healthcare field.

Recently, the H-reflex has been used by researchers in the athletic training field to evaluate the effects of musculoskeletal injuries, therapeutic modalities, and pain. Recent authors have used H-reflex to establish the presence of an arthrogenic muscle response with joint effusion. Most investigators have used the H-reflex to evaluate musculature of the leg following knee joint effusion; finding that the quadriceps H-reflex amplitude in the injured limb decreases after effusion, and can remain decreased for up to 2.5 hours. This decreased H-reflex suggests that the quadriceps muscle “shuts down,” or is inhibited, resulting in an inability to recruit as many MNs as it did prior to injury or effusion. If the H-reflex is measured properly, it can help to provide information
regarding neural function after injury. Evaluating the data from effusion studies becomes important in patients with ACL injuries because it allows clinicians to closely map neural dysfunction in a state similar to the effusion following ACL injury and allows researchers to investigate the underlying issues. However, it is more important to understand how these neural pathways are altered in an actual injured population, not just an effusion model. By investigating the spinal-reflexive loop, it may be possible to identify spinal level neurological changes in the ACLr population, allowing for future interventions to target these dysfunctions.

2.4 Corticomotor Excitability

Transcranial magnetic stimulation (TMS) is commonly used to measure cortical excitability by stimulating neural tissue to excite specific peripheral muscle tissue.\(^\text{27}\) TMS was introduced over 25 years ago by Barker et al. (1985),\(^\text{28}\) who demonstrated that it is possible to activate the corticomotor tract by a short-lasting magnetic field applied over the intact scalp in awake human subjects. This activation was easily demonstrated as a contraction of muscles on the contralateral side of the body, by measuring the latency and amplitude of the evoked potentials in electromyographic (EMG), important information about the physiology of the corticomotor tract was obtained during this early testing.\(^\text{28}\) Researchers still use the device by placing an electromagnetic coil on the participant’s skull, and into the underlying motor cortex. The device then sends magnetic pulses through the skull and into neural tissue with little irritation to the participant.\(^\text{29}\) The stimulation travels into the motor cortex, leading to a decrease in pre-synaptic inhibition, causing a down-regulation in motor-neuron pool excitability.\(^\text{27}\) This directly projects on motor neurons, increasing deliberate muscle activation, and is measured at the peripheral
muscle tissue through the use of EMG.\textsuperscript{27} Through the use of TMS, researchers can quantify a threshold of stimulation that is capable of causing a measurable muscle response, which can be defined as active motor threshold (AMT).\textsuperscript{29} If the muscle has a higher AMT, more magnetic stimulation is necessary to produce a voluntary muscle twitch, demonstrating a block or slowing in neuromuscular control.\textsuperscript{30} This outcome has been studied in numerous upper extremity muscles (i.e. hand and fingers)\textsuperscript{31}, and more recently in the lower extremity\textsuperscript{32}. Heróux and Tremblay\textsuperscript{32} used TMS to look for possible asymmetries at the corticomotor level associated with unilateral knee dysfunction after ACL injury. These studies indicated a positive correlation between muscle weakness, or neuromuscular control deficits, and higher AMT levels in participants with injury, suggesting that corticomotor excitability plays a role in altered sensory feedback of the limbs from pain, disuse or physical restriction.\textsuperscript{32}

The ease and safety of TMS has made it very popular in the investigation of human motor control and for evaluation of corticomotor reflex in patients with motor disorders. Among others, including hand and finger movements\textsuperscript{31}, this technique has briefly been used to study quadriceps neuromuscular control after injury, including ACL patients.\textsuperscript{32} Currently there is very little research regarding corticomotor excitability within an ACLr population. Exploring corticomotor excitability in patients with ACLr may give insight into the neural origins surrounding the common neuromuscular dysfunction seen following these injuries.

Recent therapeutic rehabilitation programs have focused on increasing quadriceps strength and function after ACLr and have included resistance training and dynamic functional exercises.\textsuperscript{6} Traditional strengthening programs have not been able to positively
affect persistent quadriceps weakness, which in turn, results in individuals returning to activity with prolonged neuromuscular insufficiency. Current research has hypothesized that the inhibition of neural pathways is a key factor in diminished quadriceps strength that follows ACLr. The main limitation in these studies, is that most have used simulated knee joint effusion as a model of joint injury, without establishing these neural pathway’s influence on quadriceps function in a true pathological population. There are no recent comprehensive studies evaluating how both the spinal-reflexive and corticomotor pathways are affected following ACLr, or what influence these outcomes have on quadriceps strength and neuromuscular function. Because of the poor overall outcomes associated with conventional therapeutic rehabilitation, some have suggested that targeting decreasing neural mechanisms may be needed to regain full neuromuscular function and force generating abilities of the quadriceps musculature.
Chapter 3

Methods

3.1 Study Design: Case – Control Study

The independent variables in this study included side (injured and uninjured) and group (ACLr and healthy). All participants were between 18-40 years of age and were recruited from all races and both sexes with a previous history of ACLr. All participants had unilateral anterior cruciate ligament reconstructions. All participants were cleared by a physician for full participation in physical activity. All control participants were matched on height, mass, age and sex to a participant in the ACLr group. The legs in the healthy control group were matched to the ACLr counterpart using leg dominance, defined by which leg they used to kick a ball. Participants were excluded from the study if they had a history of: concussion or head injury in the past 6 months, history of stroke, cardiac condition, epilepsy, cranial neurosurgery, migraines, cancer in the brain or thigh musculature, diagnosed psychiatric disorder; or has a cardiac pacemaker, implanted cardiac defibrillator or intracranial metallic clips. All pregnant females were excluded for protection of the fetus from electrical and magnetic stimuli. Additionally the healthy control participants were excluded if they had a history of the following: a serious
ligamentous knee injury, a lower-extremity orthopedic surgery of any kind or a serious lower extremity trauma in the past 6 months.

Three neuromuscular measurements were utilized to assess deficits of the quadriceps musculature in the injured leg and the uninjured leg of ACLr group and of both limbs in the matched healthy controls. The neuromuscular measures were taken from three major categories: A.) Corticomotor excitability measured via the active motor threshold (AMT), B.) Spinal-reflexive excitability measured via the Hoffmann reflex normalized to maximal muscle response ratio (H:M), and C.) Voluntary quadriiceps muscle activation measured via the central activation ratio (CAR). All outcome measures were performed on the same day during approximately a two-hour time period. The CAR measurement was always the last outcome measure taken because it requires the participant to produce a maximal volitional contraction, which will affect the ability of the participant to maintain a homogenous state of the nervous system during the motor evoked potential and motor neuron excitability measurements. Therefore, only the order of the first two outcome measures (active motor threshold and motor neuron excitability measurements) were randomized, followed by the central activation ratio testing. The order of leg tested (injured and uninjured) was counterbalanced for all outcome measures. For this study, the investigator was not blinded to the leg or condition of each participant, due to the visibility of the scar in the ACLr group. Prior to enrolling in the study, the participants signed an IRB approved written informed consent form.

3.2 Instrumentation

3.2.1 Spinal-reflex Excitability
Hoffmann reflex and muscle response measurements were collected with surface electromyography (MP100C BIOPAC Systems, Inc Goleta, CA). Analog to digital signal conversion was processed with a 16 bit converter (MP150, BIOPAC Systems Inc). The Acqknowledge BIOPAC Software (BIOPAC Version 3.7.3, BIOPAC Systems, Inc.) was used to visualize the signals as well as manipulate the stimuli. Signals were sampled at 1024 Hz and electromyography (EMG) amplification was set at a gain of 1000 (EMG100C BIOPAC Systems, Inc.). The common mode rejection ratio of our EMG amplifier was 100 dB and the input impedance was 2MOhms. The disk-shaped electrodes used to acquire signals were disposable, 10 mm pre-gelled Ag/AgCl (BIOPAC Systems, Inc). The electrodes were positioned 1.75 mm apart over vastus medialis muscle bellies, bilaterally. Reflexes were elicited with the BIOPAC stimulator module (STIM100A, BIOPAC Systems, Inc.), a 200 volt maximum stimulus isolation adaptor (STIMSOC BIOPAC Systems, Inc), a 2 mm shield disk electrode, (EL254S BIOPAC Systems, Inc.) and a 7 cm carbon impregnated dispersive pad.

3.2.2 Corticomotor Excitability

The Biodex System III Pro dynamometer (Biodex Medical Systems, Shirley, NY) was used to control for variations in voluntary force during testing. Motor evoked potentials (MEP) were elicited using the Magstim Rapid (Magstim Company, Wales, UK) via a double cone coil (Magstim Company, Wales, UK), and were evaluated to establish AMT. The magnetic stimulation did not exceed 1.4 Tesla (70% of stimulator output). All MEPs were measured in the peripheral muscles using the disk-shaped electrodes. The same disposable electrodes as described above were used to acquire
signals. Acqknowledge BIOPAC Software (BIOPAC Version 3.7.3, BIOPAC Systems, Inc.) was used to visualize the signals.

3.2.3 Quadriceps Voluntary Activation

The Biodex System III Pro dynamometer (Biodex Medical Systems, Shirley, NY) was also used to measure maximal voluntary force during the muscle activation testing. A square wave stimulator (S88, GRASS telefactor, W. Warwick, RI) and a stimulation isolation unit (SIU8T, W. Warwick RI) produced a 100ms train of 10 stimuli, at 100 pps, with a pulse duration of 0.6 ms, and a 0.01 ms pulse delay. The stimulation isolation unit with an estimated 3000Ω load produced an estimated 125 volts. Two 7 x 13cm Dura Stick II® (Chattanooga Group, Hixson, TN) self-adhesive electrodes were placed on the distal vastus medialis and proximal vastus lateralis and were used to deliver the stimulus to the quadriceps muscles.

3.3 Procedure

3.3.1 Participant Preparation

Prior to data collection, the vastus medialis of both limbs were shaved and debrided to ensure optimal contact. EMG electrodes were positioned 1.75 mm apart over vastus medialis muscle bellies. A ground electrode was placed on the medial malleolus of the dominant limb.

3.3.2 Maximal Voluntary Isometric Contraction (MVIC)

Strength outcomes were performed with MVIC testing, and this data was used for calculations during both corticomotor and voluntary activation testing as described below. Participants sat in the dynamometer and were positioned in 90° of hip flexion and
90° of knee flexion as measured by a hand held inclinometer (Craftsman, Hoffman Estates, IL). Non-elastic straps were secured at the lap and over the shoulder of each participant to control accessory movement during the knee extension task. The tibia, just proximal to the ankle joint, was secured to a pad on the arm of the dynamometer with a Velcro strap. Participants were instructed to cross their arms over the chest during all contractions to avoid unwanted upper extremity involvement in the task. Participants performed a series of warm-up, submaximal isometric quadriceps contractions in which they attempted to extend their knee at 25, 50 and 75% of their perceived maximal effort. Participants were then instructed to perform three MVICs in the testing position with approximately one-minute rest in between trials.

3.3.3 Corticomotor Excitability

Participants were seated in the dynamometer in the exact same position as MVIC testing. In addition, participants wore a lycra swim cap which allowed the investigator to optimally position the magnetic coil and draw lines to help visualize the positioning for the corticomotor testing. Vertical lines were drawn in the frontal and sagittal planes to identify the area of stimulation over the motor cortex.

Five percent of the previously measured MVIC was calculated and used as a standardized volitional muscle contraction during corticomotor excitability testing across all participants. To elicit an MEP on the contralateral limb, a double cone coil (Magstim Company, Wales, UK) was positioned over the vertex of the cranium and Magstim rapid (Magstim Company, Wales, UK) was used to produce a maximum magnetic stimulus of 1.4 Tesla. The coil was moved approximately 1cm in an anterior-to-posterior and
medial-to-lateral directions over the vertex until a MEP response was found and marked on the swim cap by the investigator.

Active motor threshold (AMT) referred to the lowest TMS intensity necessary to evoke a MEP in the contralateral target muscle in response to a single pulse of stimuli applied over the motor cortex.\textsuperscript{36} Active motor threshold was assessed as the lowest intensity required to elicit a MEP of $\geq 100\mu V$ amplitude in 5 out of 10 trials in the contracted muscle. At the intensity directly below AMT, the researcher needed to obtain 6 out of 10 trials in which the MEPS were $>100\mu V$ to ensure threshold was achieved. Surface EMG electrodes were positioned on the distal vastus medialis muscle of interest, as described above, and used to collect the signal elicited by the magnetic stimulation.

**3.3.4 Spinal-reflex Excitability**

The Hoffmann reflex is an electrically induced monosynaptic reflex that has been reported to be reliable in previous work (intra-class correlation coefficient [ICC3, $1=0.97$]).\textsuperscript{37} The amplitude of the Hoffmann reflex normalized to the amplitude of the muscle response has been reported to denote the excitability in the motor neuron pool.\textsuperscript{16} Although motor neuron pool excitability may differ between people, bilateral differences within the same person have been reported in the past to determine differences in motor neuron pool excitability between legs.\textsuperscript{38} We do understand that the relative limitation in assessing deficits in this manner is that bilateral deficits in neuromuscular mechanisms may be present following a unilateral joint injury;\textsuperscript{39} yet, this issue cannot be resolved without changing this study to prospective in nature which may introduce other concerns. In order to change the current study to prospective in nature, we would need to prescreen a number of individuals and wait until they were injured, which is not practical for time
and personnel reasons. Therefore, our inclusion of a healthy matched control group will allow us to determine if bilateral deficits within the ACLr are different than a healthy, uninjured control group.  

Participants were instructed to lie supine on a padded treatment plinth with their arms comfortably placed at their side with their head in a neutral position. The head of each participant rested comfortably on a pillow and their knees slightly flexed (~10-15°) with the support of a half bolster. The hair over the collection sites was shaved and the skin over the recording electrode site was debrided and cleaned with an alcohol prep pad. Two 10mm, pre-gelled Ag-AgCl (EL503, BIOPAC Systems Inc) surface electromyography electrodes were position 2cm apart over the distal vastus medialis to measure EMG activity. A 2mm shielded disc stimulating electrode (EL2524S, BIOPAC Systems Inc) was positioned over the femoral nerve and secured with hypoallergenic tape and a 3x3cm self-adhesive electrode was positioned over the hamstring and used as a dispersive electrode. A 1ms square wave stimulus was produced with a BIOPAC stimulator module (STM100A, BIOPAC Systems, Inc) and a 200 volt maximum stimulus adaptor (STMISOC, BIOPAC Systems Inc) and delivered to the femoral nerve.

During testing participants were instructed to maintain a constant head, eye and hand position by focusing on a circle on the ceiling. The stimulus was increased in 0.2volt increments until a maximum Hoffmann reflex was elicited. Three maximal Hoffman reflexes were collected at that voltage and averaged for analysis. The stimulus was then increased until a maximal muscle response was elicited, in which 3 maximal muscle responses were then elicited and averaged for analysis. Intensity was increased until a maximal muscle response was elicited, and 3 were recorded. The average of the
three maximal Hoffmann reflexes were then normalized to the average of the three muscle responses, creating the H:M outcome variable.

3.3.5 Measurements of Quadriceps Voluntary Activation (CAR)

The central activation ratio measures the combination of motor unit firing rate and motor unit recruitment in the assessment of quadriceps activation.\textsuperscript{20} Although the CAR provides a valid estimation of the percentage of motor units able to activate the muscle, it is unable to distinguish what mechanisms are causing recruitment failure.

The Biodex System III dynamometer (Biodex Medical Systems, Shirley, NY) was used to measure maximal voluntary force during the muscle activation testing. Participants were positioned exactly the same as described above for MVIC and corticomotor testing. Two 7x13cm self-adhesive stimulating electrodes were positioned on the proximal vastus lateralis (with the medial border of the electrode aligned with the anterior superior iliac spine at the height of the greater femoral trochanter) and the distal vastus medialis (with the lateral border of the electrode bisecting the patella 1.5 inches superior to the superior patellar pole).

Participants performed a series of warm-up, submaximal isometric quadriceps contractions in which they attempted to extend their knee at 25, 50 and 75% of their perceived maximal effort. During this warm-up period, participants received submaximal electrical stimulation at 25, 50 and 75% of the maximal 125 volts (100ms train of 10 stimuli, at 100 pps, with pulse duration of 0.6 ms, and a 0.01 ms pulse delay) for familiarization purposes.\textsuperscript{41-43} Following the practice trials, the participants performed three MVICs, with a supramaximal automated stimulus triggered once the participant reached a plateau in torque. An increase in torque output following the electrical
stimulation denoted the presence and magnitude of quadriceps activation failure. CAR was calculated as a ratio comparing the participant’s maximal voluntary torque output to the maximal torque produced with the supramaximal stimulus.

### 3.3.6 Statistical Analysis

Prior to statistical analysis, independent t-tests were run between demographic variables to assess demographic differences between groups. Three separate 2x2 mixed model ANOVAs were used to assess differences between leg and group for H:M, AMT, and CAR independently. Post hoc paired samples t-tests were run in the detection of a significant interaction. In addition, inter-limb difference scores for each variable were calculated between injured and uninjured limb (inter-limb difference score = injured limb – uninjured limb) for the ACLr group. Three separate Spearman rank correlation analyses were performed to determine statistically significant relationships between H:M, AMT and CAR inter-limb difference scores.
Chapter 4

Results

4.1 Participants

Fifty-three participants were recruited between the ages of 18 and 40. Demographic data from the participants is located in Table 1. Age (p = 0.23), height (p = 0.81), mass (p = 0.97), Tegner (p=0.53) and LEFS (p = 0.61) did not significantly differ between ACLr and control groups. There was a significant difference found in IDKC scores between groups (p≤ 0.001). All participants completed the full testing session, which led to a dropout rate of 0%.

4.2 Group by Leg Differences

Means and standard deviations of AMT, H:M and CAR for each group can be found in Table 2.

A significant interaction effect was found for AMT (p = 0.027). Post hoc analysis revealed that the injured limb of the ACLr group demonstrated higher AMT values than the uninjured limb of the ACLr group (p=0.019). No difference in AMT was detected between the matched injured and uninjured limbs of the control group (p= 0.501). There were also no differences in AMT between the uninjured limb of the ACLr group and the matched uninjured limb of the control group (p= 0.561), or between the injured limb of the ACLr group and the matched uninjured limb of the control group (p= 0.422).

No significant differences were found between group or limb for H:M (p = 0.628)
or CAR (p=0.285).

4.3 Relationship Between Inter-limb Difference Scores

There was a significant, negative moderate relationship between H:M and CAR inter-limb difference scores ($\rho = -0.436, p = 0.026$). No significant relationship was found between H:M and AMT inter-limb difference scores ($\rho = -0.158, p = 0.441$) or between AMT and CAR inter-limb difference scores ($\rho = -0.036, p = 0.862$).

Table 4.1 Subject Demographics

<table>
<thead>
<tr>
<th></th>
<th>ACLr</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>n</strong></td>
<td>27</td>
<td>26</td>
</tr>
<tr>
<td><strong>Sex</strong></td>
<td>M: 9</td>
<td>F: 18</td>
</tr>
<tr>
<td><strong>Age (years)</strong></td>
<td>20.81 ± 1.86</td>
<td>21.19 ± 4.92</td>
</tr>
<tr>
<td><strong>Height (cm)</strong></td>
<td>170.92 ± 10.39</td>
<td>171.55 ± 8.72</td>
</tr>
<tr>
<td><strong>Mass (kg)</strong></td>
<td>72.39 ± 14.45</td>
<td>72.24 ± 16.92</td>
</tr>
<tr>
<td><strong>Months Post ACLr</strong></td>
<td>24.88 ± 32.09</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>IKDC</strong></td>
<td>84.6 ± 9.6*</td>
<td>99.5 ± 1.13*</td>
</tr>
<tr>
<td><strong>Activity Level (Tegner)</strong></td>
<td>6.15 ± 1.94</td>
<td>5.84 ± 1.59</td>
</tr>
<tr>
<td><strong>LEFS</strong></td>
<td>77.61 ± 5.08</td>
<td>78.23 ± 3.30</td>
</tr>
</tbody>
</table>

Values are reported as means ± standard deviations.
Abbreviations: ACLr, anterior cruciate ligament reconstruction; IKDC, International Knee Documentation Committee form; LEFS, Lower Extremity Functional Scale
* denotes a significant difference found in IKDC scores between groups (p ≤ 0.001)
Table 4.2 AMT, H:M and CAR ANOVA Results

<table>
<thead>
<tr>
<th></th>
<th>ACLr Injured</th>
<th>ACLr Uninjured</th>
<th>Control Injured</th>
<th>Control Uninjured</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMT (% Tesla)</td>
<td>40.9 ± 16.1*</td>
<td>36.9 ± 14.9*</td>
<td>37.3 ± 10.6</td>
<td>38.0 ± 9.8</td>
</tr>
<tr>
<td>H:M</td>
<td>0.233 ± 0.149</td>
<td>0.252 ± 0.176</td>
<td>0.243 ± 0.142</td>
<td>0.250 ± 0.145</td>
</tr>
<tr>
<td>CAR</td>
<td>0.905 ± 0.109</td>
<td>0.905 ± 0.121</td>
<td>0.884 ± 0.147</td>
<td>0.898 ± 0.123</td>
</tr>
</tbody>
</table>

Values are reported as means ± standard deviations.
Abbreviations: ACLr, anterior cruciate ligament reconstruction; AMT, active motor threshold; H:M, Hoffmann reflexes normalized to maximal muscle responses; CAR, central activation ratio.
* denotes a significantly higher AMT than the uninjured limb in the ACLr group (p = 0.019)
Chapter 5

Discussion

The primary purpose of this study was to investigate if ACLr participants present with alterations in quadriceps corticomotor excitability, spinal-reflexive excitability, and voluntary activation of their injured limb compared to their uninjured limb and healthy matched controls. Although no differences were found in spinal-reflexive excitability or quadriceps muscle activation, the injured limb of the ACLr group demonstrated lower corticomotor excitability (denoted by higher AMT) compared to the uninjured limb. Our secondary objective was to determine the relationship between inter-limb differences in corticomotor excitability, spinal-reflexive excitability, and voluntary quadriceps activation in the ACLr participants. A significant and negative relationship was discovered between spinal-reflexive excitability and voluntary activation inter-limb difference scores.

5.1 Differences in Corticomotor Excitability Between ACLr Limbs

In our current study, we utilized AMT as a measure of corticomotor excitability. Through the use of TMS, we defined AMT as a threshold of stimulation that is capable of causing a measureable muscle response.\textsuperscript{29,36} In this scenario, higher AMT values, which means more magnetic stimulation was necessary to produce a voluntary muscle
twitch, demonstrates a block or slowing in corticomotor excitability.\textsuperscript{30} This outcome has been studied in numerous upper extremity muscles (i.e. hand and fingers)\textsuperscript{31}, and more recently in the lower extremity.\textsuperscript{32} Heróux and Tremblay\textsuperscript{32} used resting thresholds, as compared to AMT used in our study, to look for possible asymmetries at the corticomotor level associated with unilateral knee dysfunction after ACL injury. These studies indicated a positive correlation between muscle weakness, or neuromuscular control deficits, and higher resting threshold levels in participants with injury, suggesting that corticomotor excitability plays a role in altered sensory feedback of the limbs from pain, disuse or physical restriction.\textsuperscript{32}

Other studies have investigated altered brain activity after ACLr. In 2008, Baumeister et al.\textsuperscript{44} explored changes in cortical activity after ACLr in respect to joint position. They found an alterations in electroencephalography, specifically noting an increase in frontal Theta spectral power and decreases in parietal Alpha-2 power after ACLr.\textsuperscript{44} They argued that mechanoreceptors in the knee were either lost or damaged in the involved knee after ACLr and that these knee joint changes caused alterations in peripheral afferent sensory information, which in turn led to altered processing in the brain and therefore indicating modifications in the CNS.\textsuperscript{45} In a recent neuroimaging (MRI) study, Kapreli et al.\textsuperscript{46} demonstrated that ACL deficient (ACLd) patients had alterations in several sensorimotor brain areas compared to the control group.\textsuperscript{46} Although those studies investigated two different ACL populations (ACLr vs. ACLd), these data support our finding that alterations in brain function are present after ACL injury.

In 2011, further research by Baumeister et al.\textsuperscript{45} again found significantly higher frontal Theta spectral power values compared to the healthy control group; whereas
increased frontal Theta power associated with ACLr may reflect a higher focused attention during the force matching task, and therefore a higher neurocognitive involvement. The ACLr patients in that particular study were able to reach the same force production during a seated task compared to the healthy group; however, they needed to use more neurocognitive resources to produce the same muscle force. Our results indicate that the injured limb of the participants in the ACLr group had higher AMT values when compared to the uninjured limb of the ACLr group (p = 0.019). Therefore, participants with ACL reconstructions needed higher stimulation levels over the motor cortex to elicit a voluntary muscle twitch in the vastus medialis muscle in their injured limb. Results from this current study, as well as studies from Baumeister, suggest alterations in corticomotor pathways following ACL injury. If more corticomotor resources were needed to produce higher force values in an ACLr population, as Baumeister discovered, and ACLr individuals are experiencing deficits in corticomotor drive, as we have revealed, targeting corticomotor excitability during rehabilitation may benefit these patients. Future research still needs to determine how corticomotor excitability is altered following ACLr. Examining the effect of targeting corticomotor deficits, through interventions such as biofeedback, has on increasing function in ACLr patients will be critically important.

5.2 No Deficits Observed in Voluntary Activation

In this study, we did not observe significant differences in spinal-reflexive excitability or voluntary quadriceps activation between limbs or between groups. Quadriceps activation (QA) after ACL injury and reconstruction is a phenomenon with important clinical implications in patients rehabilitating from knee joint injury. In 2010, Hart et al.
published a systematic review describing quadriceps activation differences following knee injury. This research team found that on average, QA deficits were found in both ACLd and ACLr populations when compared with the healthy control population. This study also found that weighted mean CAR values were higher in the ACLd population than in the ACLr population, while the prevalence of QA failure was more than double in the ACLd patients compared with the ACLr patients. These quadriceps activation deficits can be a result of arthrogenic muscle inhibition (AMI), which is a typical consequence of joint injury when the body’s protective, reflexive, and unconscious responses respond in a manner that alters neural drive to the surrounding musculature due to pain. Hurley et al. suggested that AMI is due to altered afferent input originating from mechanoreceptors within the injured motor neurons, therefore causing incomplete muscle activation. Other factors, such as pain and disuse, may also contribute to quadriceps inhibition after joint injury.

Our current results suggest that ACLr individuals in our study did not experience deficits in voluntary activation, which are in disagreement with majority of the literature. One potential reason for this insignificant finding is the unexpectedly low CAR values for our control group. A CAR cutoff of 90% has previously been thought as a threshold for activation deficits, and as seen in Table 2, both of our groups met this cutoff. This means that although the average of our ACLr group was experiencing activation deficits, our control group appeared to be as well, minimizing the ability to detect significant differences between groups. Seeing as our control group needed to be free from previous injury and did not differ from our ACLr group on activity level, it is unclear why this group of people does not match the healthy population average as reported in previous
literature. Other potential explanations for our insignificant findings could be due to our subject demographics and ACLr patient’s functional level. Our ACLr individuals were at a variety of time points post-surgery. Although this makes this research very generalizable among the entire ACLr population, those who are further from surgery may have higher activation levels compared to those who may have just been cleared for participation.

5.3 No Deficits Observed in Spinal-reflexive Excitability

Investigating the spinal-reflexive loop in an ACLr population would allow identification of spinal level changes. Much of the previous literature regarding quadriceps spinal-reflexive excitability in regards to knee injury has utilized an experimental knee effusion model to assess differences. Hopkins et al.\textsuperscript{33} investigated spinal-reflexive excitability in a knee joint effusion study, where patients voluntarily had 30mL of sterile saline injected into their joint capsule to mimic joint effusion after injury. Before the 30mL of artificial knee effusion, a maximum H-reflex was recorded for the quadriceps (vastus medialis) and soleus muscles. H-reflex measurements were taken 30, 90, 150, and 210min intervals post effusion.\textsuperscript{33} All soleus H-reflex measures after effusion increased compared with the pre-effusion measure time point (p<0.05).\textsuperscript{33} An overall difference was detected in vastus medialis H-reflex measures over time (p=0.0001).\textsuperscript{33} All vastus medialis H-reflex measures after effusion decreased compared with the pre-effusion measure (p< 0.05).\textsuperscript{33} This data, and others\textsuperscript{8,23,33}, suggests significant inhibition and reduction in spinal-reflexive excitability of the vastus medialis after artificial knee effusion.
Although joint effusion models near unanimously show deficits in quadriceps spinal-reflexive excitability, minimal research has been performed in an injured population. Hoffmann et al.\textsuperscript{48} found ACLr individuals to have significantly weaker quadriceps strength compared to the control group, demonstrating persistent quadriceps strength deficits in the ACLr population. However, no significant spinal-reflexive excitability differences were found between the groups, or limb.\textsuperscript{48} Hoffmann, however, utilized the soleus for H-reflex testing,\textsuperscript{48} and did not measure spinal-reflexive excitability in the quadriceps, recommending future research to examine spinal-reflex excitability of the quadriceps. To our knowledge, this is the first study to examine quadriceps spinal-reflexive excitability within an ACLr population, and our results support Hoffmann’s\textsuperscript{48} findings that no significant differences in spinal-reflexive excitability are seen between ACLr and healthy participants. In addition, our study included 27 ACLr participants, where most effusion models have low sample size, such as the Hopkins\textsuperscript{23} paper which only included 8 participants.

\textbf{5.4 Relationship of Spinal-reflexive Excitability, Corticomotor Excitability and Voluntary Activation Inter-limb Difference Scores in ACLr Population}

The results of our investigation revealed a significant, negative moderate relationship between H:M and CAR inter-limb difference scores ($\rho = -0.436$, $p = 0.026$). It is important to note that these correlations were performed between inter-limb difference scores, where a positive inter-limb difference score indicates an up-regulation in that value compared to the uninjured limb. The negative relationship observed between spinal-reflexive excitability and voluntary activation means that individuals who have deficits in voluntary activation (negative inter-limb difference score for CAR) appear to
have up-regulated spinal-reflexive excitability (higher inter-limb difference scores for H:M). The up regulated H:M may be due to the fact that the participants are trying to maintain QA throughout the testing session. If the injured limb of the ACLr participant is experiencing deficits in activation, the nervous system may strive to up-regulate spinal-reflexive capabilities in an attempt to increase voluntary activation for that limb.

Although a significant relationship was found between spinal-reflexive excitability and voluntary activation, no other significant relationships were discovered. This finding is especially interesting, considering no limb differences were observed in spinal-reflexive excitability and voluntary activation between limbs of the ACLr group, however a difference in corticomotor excitability was discovered. This requires one to question, if differences exist in corticomotor excitability, and no relationship existed between corticomotor excitability and the spinal-reflexive pathway or muscle activation, what clinical significance do these corticomotor deficits have? This is difficult to interpret, as this investigation focused on a gross measure of corticomotor excitability, which is discussed further in our limitations section. Regardless, future research is warranted to understand the true relationship between these movement generating pathways, and the effect they have on neuromuscular dysfunction seen following ACLr.

5.5 Limitations

Participant demographics can be described as a limitation to this study because there was a very wide range of ACLr patients used. For example, average time post-reconstruction for our ACLr group was 24.88 ± 32.09 months, three different graft types were used in our 27 ACLr participants, and the average IKDC and LEFS scores were 84.6 ± 9.6 and 77.61 ± 5.08 respectively. The wide range of months post-surgery (6
months – 11 years) may be seen as a limitation; however our goal was to gain a general representative sample of ACLr participants, which we feel we accomplished. Future investigations could benefit from including ACLr participants at specific time points following surgery to understand the progression of these dysfunctions.

Another limitation is that our study was a retrospective analysis of the ACLr population. This was a limitation because we could not quantify the participant’s muscle activation, spinal-reflex excitability, or corticomotor excitability prior to injury or surgery; therefore it is hard to determine if there were AMT deficits prior to injury. A prospective or longitudinal evaluation of these outcomes may provide new insight.

Our methods of quantifying corticomotor excitability may also be considered a limitation, as assessing levels of corticomotor and spinal reflex excitability is highly dependent on the mental state of the participant being tested. During the testing session, each participant was instructed to relax as much as possible, remain quiet, and clear his or her mind. Individual changes in the participant’s state of mind could affect their neural activity, which could increase or decrease outcome measures during the testing session. However, we utilized very controlled methods to ensure that each participant was relaxed and in the same neurological state between different participants. In addition, utilizing AMT as a gross measure of cortical excitability could be seen as a limitation. Motor evoked potential values, measures of intracortical inhibition, alpha motor neuron inhibition, or stimulus response curves may provide new information regarding corticomotor pathways in an ACLr population and should be utilized in future investigations.

5.6 Future Research
More research is necessary to fully determine why these neuromuscular deficits arise after ACL injury and reconstruction. Utilizing a prospective approach to this study would be helpful to determine if the patients had deficits in AMT prior to injury; however it would be difficult to perform since there would need to be a very large subject size in order to test those who may or may not become injured over time. This study found AMT differences in this specific ACLr population at varying time points after injury and surgery. It would be helpful for future researchers to take a more longitudinal approach to follow these measures after injury to adequately track neural differences as the patient progresses through stages of injury and healing.

Variation in therapeutic rehabilitation after surgery is also another area that researchers could focus on in order to target this injured population. A structured rehabilitation program would be beneficial for researchers so that they could standardize each participant’s rehabilitation in the same manner as the other participants. Our observed corticomotor deficits could potentially be traced back to rehabilitation techniques and intensity of the therapeutic program.

Transcranial magnetic stimulation has contributed substantially to our understanding of motor physiology, and there is every reason to believe that it will do so in the future. Altering this study in a way to test participants at varying times post injury or surgery may result in a better overall depiction of the neural alterations following injury and surgery. This study has shown that it is vital for future researchers to find out what is causing AMT differences in this injured population, and how other neural pathways contribute to neuromuscular deficits seen following ACLr.

5.7 Conclusion
We looked to determine if ACLr individuals presented with deficits in quadriceps corticomotor excitability, spinal-reflexive excitability, and voluntary quadriceps activation. Active motor thresholds were shown to be higher in the injured limb of the ACLr population, demonstrating deficits in corticomotor excitability within an ACLr population. We also found a relationship between spinal-reflexive excitability and voluntary activation inter-limb difference scores of an ACLr population, potentially revealing an up-regulation of neural pathways post injury. Although the results of this investigation are promising, more research is needed to examine how neural alterations progress during ACL injury, and to determine the extent to which neural alterations affect function post ACLr.
References


Appendix A

Informed Consent for Human Research

ADULT RESEARCH SUBJECT INFORMATION AND CONSENT FORM

NEURAL EXCITABILITY OF THE LOWER EXTREMITY FOLLOWING UNILATERAL KNEE AND ANKLE INJURY

Principal Investigator: Brian Pietrosimone PhD, ATC
Other Staff (Co-Investigator): Phillip Gribble PhD, ATC, Andrew Meszaros PhD PT, Adam Lepley MS ATC, Hayley Ericksen MS, ATC, Amy Clements ATC

Contact Phone number(s): (419) 530-4467

What you should know about this research study:

- We give you this consent/authorization form so that you may read about the purpose, risks, and benefits of this research study. All information in this form will be communicated to you verbally by the research staff as well.
- Routine clinical care is based upon the best-known treatment and is provided with the main goal of helping the individual patient. The main goal of research studies is to gain knowledge that may help future patients.
- We cannot promise that this research will benefit you. Just like routine care, this research can have side effects that can be serious or minor.
- You have the right to refuse to take part in this research, or agree to take part now and change your mind later.
- If you decide to take part in this research or not, or if you decide to take part now but change your mind later, your decision will not affect your routine care.
• Please review this form carefully. Ask any questions before you make a
decision about whether or not you want to take part in this research. If you
decide to take part in this research, you may ask any additional questions
at any time.
• Your participation in this research is voluntary.

PURPOSE (WHY THIS RESEARCH IS BEING DONE)

You are being asked to take part in a research study looking at the nerve function of leg,
thigh and hip muscles. The purpose of the study is to determine if people with a
previous knee or ankle injuries as well as people without a previous joint injury
have different nerve excitability between legs.
You were selected as someone who may want to take part in this study because you
have chronic ankle instability or have had an anterior cruciate ligament reconstruction to
one knee or you have never had a knee injury before. There will be approximately 120
people participating in this study at the University of Toledo.
DESCRIPTION OF THE RESEARCH PROCEDURES AND DURATION OF YOUR INVOLVEMENT

If you decide to take part in this study, you will be asked to report to the Joint Injury and Muscle Activation (JIMA) Laboratory in the Health Science and Human Services building (Room 1409). You will be asked to fill out Knee Injury/Ankle Injury Questionnaires about how your knee/ankle feels during different activities. We will then test the neural function of both of your legs using 3 different methods. These methods include muscle activation testing, Reflex Testing and Motor Cortex Testing. This study will consist of one session lasting approximately 2 hours.

Ankle and Knee Injury Questionnaires
You will be asked to provide us information regarding your previous history of your joint injury, current and past level of activity and how your joint injury currently affects you during different activities.

Muscle Activation Testing
You will be asked to stand near the testing chair and two electrodes treated with some gel will be place on your thigh. One of the electrodes will be placed above your knee and the other will be given to you to place below your hips so that it lies flat when you are sitting. The electrodes will be held in place with an elastic bandage. These electrodes will be used to deliver a brief, mild electrical stimulus to your thigh muscles. The electricity will be approximately a half a second in duration and will contract your thigh muscle for that half second and relax.

You will be asked to sit in a chair that resembles a car seat. You will have a seat belt applied so that you do not move as you are contracting your leg muscles as hard as you can. You will then be asked to extend your leg as hard as you can and hold it for five seconds. While you are extending out the electrical stimulus will be delivered to your thigh. This stimulus feels similar to a static electric shock that you could get from walking across a carpet in a dry room and then touching a doorknob, although the voltage is lower. You will be asked to perform this at least three times at 5 different periods throughout each session at 3 different positions on both legs. You will be allowed up to 1 minute of rest between each repetition.

Reflex Testing
This testing provides an estimate of how well nerves in the lower leg are functioning. You will be instructed to stand on your dominant leg or lie on a table. You will have sticky electrodes placed on your lower legs and thigh. These
electrodes are called EMG electrodes which stand for Electromyography which is a recording of the electrical (reflex) activity in skeletal muscle. The sites of the EMG electrodes will be shaved and cleaned with alcohol. An electrode that provides a stimulus will be taped behind your knee and in the front of your hip. Several reflex measurements will be taken while you are balancing or lying down.

- These measurements include a 1-millisecond stimulus.
- The intensity of this stimulus will vary depending on the reflex being elicited.
- The stimuli in this study feel similar to static electricity felt as you touch a door knob after walking across a carpet.
- A series of measurements will be taken on both legs

**Motor Cortex Testing**
This testing provides us important information regarding how your brain is sending messages to muscles in your legs. You will be asked to lie on a table with you hands at your side. We will position a coil over your head and adjust the position of the coil until it is in the correct spot. We will ask you to wear a bathing cap and ear plugs. A brief magnetic stimulus will then be produced which will sound like a “click.” You will not have and associated pain or discomfort in your head, but rather may feel a brief muscle contraction in the muscles of your leg or thigh. You will be asked to flex certain leg muscles at a small to moderate intensity while we provide a series of brief magnetic stimuli to your head.

**RISKS AND DISCOMFORTS YOU MAY EXPERIENCE IF YOU TAKE PART IN THIS RESEARCH**

**Likely Risks**
- Mild discomfort for a very brief period during the electrical stimulation.

**Less Likely Risks**
- Mild, transient skin irritation from the sticky electrodes.

**Very Unlikely Risks**
- Mild, transient headache following magnetic stimulation
- In people with a history of seizures there is a slight possibility of causing a seizure with the magnetic stimulation, therefore you must tell us prior to testing if you have ever had a seizure so we can exclude you from the study.
POSSIBLE BENEFIT TO YOU IF YOU DECIDE TO TAKE PART IN THIS RESEARCH

Although information that is gained from this research that may be used to assess and treat various ankle injuries, we cannot and do not guarantee or promise that you will receive any benefits from this research.

RISKS TO UNBORN CHILDREN

It is unknown how the electrical stimulation used in this study would affect an unborn fetus, therefore, if you are pregnant you will not be allowed to participate in this study.

COST TO YOU FOR TAKING PART IN THIS STUDY

You are not directly responsible for making any type of payment to take part in this study. However, you are responsible for providing the means of transportation to the Joint Injury and Muscle Activation Laboratory. You will not be compensated for gas for travel or any other expenses to participate in this study.

PAYMENT OR OTHER COMPENSATION TO YOU FOR TAKING PART IN THIS RESEARCH

You will not be compensated for participating in this study.

ALTERNATIVE(S) TO TAKING PART IN THIS RESEARCH

The only alternative is not to participate in this study.

CONFIDENTIALITY - (USE AND DISCLOSURE OF YOUR PROTECTED HEALTH INFORMATION)

By agreeing to take part in this research study, you give to The University of Toledo (UT), the Principal Investigator and all personnel associated with this research study your permission to use or disclose health information that can be identified with you that we obtain in connection with this study. We will use this information to for the purpose of conducting the research study as described in the research consent/authorization form.

The information that we will use or disclose includes history of knee joint injury, activity level, and strength or muscle activation measurements. We may use this information ourselves, or disclose this information as part of a research study. Under some circumstances, the Institutional Review Board and Research and Sponsored Programs of the University of Toledo may review your information for compliance audits. We may
also disclose your protected health information when required by law, such as in response to judicial orders.

The University of Toledo is required by law to protect the privacy of your health information, and to use or disclose the information we obtain about you in connection with this research study only as authorized by you in this form. There is a possibility that the information we disclose may be re-disclosed by the persons we give it to, and no longer protected. However, we will encourage any person who receives your information from us to continue to protect and not re-disclose the information.

Your permission for us to use or disclose your protected health information as described in this section is voluntary. However, you will not be allowed to participate in the research study unless you give us your permission to use or disclose your protected health information by signing this document.

You have the right to revoke (cancel) the permission you have given to us to use or disclose your protected health information at any time by giving written notice to Dr. Brian Pietrosimone, MS119 2801 W. Bancroft St. Toledo, OH 43606. However, a cancellation will not apply if we have acted with your permission, for example, information that already has been used or disclosed prior to the cancellation. Also, a cancellation will not prevent us from continuing to use and disclose information that was obtained prior to the cancellation as necessary to maintain the integrity of the research study.

Except as noted in the above paragraph, your permission for us to use and disclose your protected health information will stop at the end of the research study. A more complete statement of University of Toledo’s Privacy Practices is set forth in its Joint Notice of Privacy Practices. If you have not already received this Notice, a member of the research team will provide this to you. If you have any further questions concerning privacy, you may contact the University of Toledo’s Privacy Officer at 419-383-3413.

IN THE EVENT OF A RESEARCH-RELATED INJURY

In the event of injury resulting from you taking part in this study, treatment can be obtained at a health care facility of your choice. You should understand that the costs of such treatment will be your responsibility. Financial compensation is not available through The University of Toledo or The University of Toledo Medical Center. By signing this form you are not giving up any of the legal rights of your son/daughter/legal charge as a research subject. In the event of an injury, contact Brian Pietrosimone, PhD, ATC (419) 530-4467
**VOLUNTARY PARTICIPATION**

Taking part in this study is voluntary. You may refuse to participate or discontinue participation at any time without penalty or a loss of benefits to which you are otherwise entitled. If you decide not to participate or to discontinue participation, your decision will not affect your future relations with the University of Toledo or The University of Toledo Medical Center.

**NEW FINDINGS**

You will be notified of new information that might change your decision to be in this study if any becomes available.

**ADDITIONAL ELEMENTS**

There is no other additional information for this study. _____

**OFFER TO ANSWER QUESTIONS**

Before you sign this form, please ask any questions on any aspect of this study that is unclear to you. You may take as much time as necessary to think it over. If you have questions regarding the research at any time before, during or after the study, you may contact: Dr. Brian Pietrosimone- (419) 530-4467. If you have questions beyond those answered by the research team or your rights as a research subject or research-related injuries, please feel free to contact the Chairperson of the University of Toledo Biomedical Institutional Review Board at 419-383-6796.

**SIGNATURE SECTION (Please read carefully)**

YOU ARE MAKING A DECISION WHETHER OR NOT TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES THAT YOU HAVE READ THE INFORMATION PROVIDED ABOVE, YOU HAVE HAD ALL YOUR QUESTIONS ANSWERED, AND YOU HAVE DECIDED TO TAKE PART IN THIS RESEARCH.

BY SIGNING THIS DOCUMENT YOU AUTHORIZE US TO USE OR DISCLOSE YOUR PROTECTED HEALTH INFORMATION AS DESCRIBED IN THIS FORM.

The date you sign this document to enroll in this study, that is, today’s date, MUST fall between the dates indicated on the approval stamp affixed to the bottom of each page. These dates indicate that this form is valid when you enroll in the study but do not reflect how long you may participate in the study. Each page of this Consent/Authorization Form is stamped to indicate the form’s validity as approved by the UT Biomedical Institutional Review Board (IRB).

Name of Subject (please print) ____________________________ Signature of Subject or Person Authorized to Consent ____________________________ Date __________ a.m. __________ p.m.

Relationship to the Subject (Healthcare Power of Attorney authority or Legal Guardian) ____________________________ Time __________ a.m. __________ p.m.
<table>
<thead>
<tr>
<th>Name of Person Obtaining Consent (please print)</th>
<th>Signature of Person Obtaining Consent</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name of Witness to Consent Process (when required by ICH Guidelines) (please print)</th>
<th>Signature of Witness to Consent Process (when required by ICH Guidelines)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

YOU WILL BE GIVEN A **SIGNED** COPY OF THIS FORM TO KEEP.
Appendix B

TMS Exclusion Criteria Form

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concussion or head injury in the past 6 months</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Stroke</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Cardiac Condition</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Epilepsy</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Cranial Neural Surgery</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Cancer in the brain or thigh musculature</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Diagnosed psychiatric disorder</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>A cardiac pacemaker</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Implanted cardiac defibrillator</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Intracranial metallic clips</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
Appendix C

Knee Injury History Form
Knee Injury History Form
Joint Injury & Muscle Activation Laboratory
University of Toledo

Subject Number ___________________________  Date ____________

Please Circle (Yes or No) regarding your situation.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Have you had an injury to either leg that has altered you function in the past 6 months?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Have you had a surgery to either leg (knee, ankle, hip) in the past six months (other than menisectomy)?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Do you have any knee ligaments that have not been reconstructed?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Do you have any nerve injuries in your legs or lower back?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Do you have any known muscular abnormalities?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Do you have a heart condition that would stop you from exercising?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Have you ever been diagnosed with cancer over your knee or thigh?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Do you currently have an infection over your thigh or in your knee?</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Do you know of a hypersensitivity to electrical stimulation?</td>
</tr>
</tbody>
</table>

1. **Have you ever had a knee injury?**
   
   When (month / year): ___________________________
   
   Explain: ________________________________________

2. **Have you ever had a knee Surgery?**
   
   When (month / year): ___________________________
   
   Explain: ________________________________________

   If ACL Reconstruction, What graft type? ___________________________________________________________________

3. **Did you participate in physical therapy or therapeutic exercise?**
   
   When did you start (month / year): _______________________
   
   For How Long: _______________________

4. **Have you ever had an injury/surgery to you ankle, hip or lower back?**
   
   When (month/ year): ___________________________
   
   Explain: ________________________________________
Appendix D

International Knee Documentation Committee Form
2000 IKDC SUBJECTIVE KNEE EVALUATION FORM

Your Full Name: ____________________________

Today's Date: ______/_______/_______ Date of Injury: ______/_______/_______

Day Month Year Day Month Year

SYMPTOMS*:
*Grade symptoms at the highest activity level at which you think you could function without significant symptoms, even if you are not actually performing activities at this level.

1. What is the highest level of activity that you can perform without significant knee pain?
   - Very strenuous activities like jumping or pivoting as in basketball or soccer
   - Strenuous activities like heavy physical work, skiing or tennis
   - Moderate activities like moderate physical work, running or jogging
   - Light activities like walking, housework or yard work
   - Unable to perform any of the above activities due to knee pain

2. During the past 4 weeks, or since your injury, how often have you had pain?

   10  9  8  7  6  5  4  3  2  1  0  Constant

   Never

3. If you have pain, how severe is it?

   10  9  8  7  6  5  4  3  2  1  0  Worst pain imaginable

   No pain

4. During the past 4 weeks, or since your injury, how stiff or swollen was your knee?

   - Not at all
   - Mildly
   - Moderately
   - Very
   - Extremely

5. What is the highest level of activity you can perform without significant swelling in your knee?

   - Very strenuous activities like jumping or pivoting as in basketball or soccer
   - Strenuous activities like heavy physical work, skiing or tennis
   - Moderate activities like moderate physical work, running or jogging
   - Light activities like walking, housework, or yard work
   - Unable to perform any of the above activities due to knee swelling

6. During the past 4 weeks, or since your injury, did your knee lock or catch?

   Yes  No

7. What is the highest level of activity you can perform without significant giving way in your knee?

   - Very strenuous activities like jumping or pivoting as in basketball or soccer
   - Strenuous activities like heavy physical work, skiing or tennis
   - Moderate activities like moderate physical work, running or jogging
   - Light activities like walking, housework or yard work
   - Unable to perform any of the above activities due to giving way of the knee
SPORTS ACTIVITIES:

8. What is the highest level of activity you can participate in on a regular basis?

☐ Very strenuous activities like jumping or pivoting as in basketball or soccer
☐ Strenuous activities like heavy physical work, skiing or tennis
☐ Moderate activities like moderate physical work, running or jogging
☐ Light activities like walking, housework or yard work
☐ Unable to perform any of the above activities due to knee

9. How does your knee affect your ability to:

<table>
<thead>
<tr>
<th>Activity</th>
<th>Not difficult at all</th>
<th>Minimally difficult</th>
<th>Moderately Difficult</th>
<th>Extremely difficult</th>
<th>Unable to do</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Go up stairs</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>b. Go down stairs</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>c. Kneel on the front of your knee</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>d. Squat</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>e. Sit with your knee bent</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>f. Rise from a chair</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>g. Run straight ahead</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>h. Jump and land on your involved leg</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>i. Stop and start quickly</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

FUNCTION:

10. How would you rate the function of your knee on a scale of 0 to 10 with 10 being normal, excellent function and 0 being the inability to perform any of your usual daily activities which may include sports?

FUNCTION PRIOR TO YOUR KNEE INJURY:

<table>
<thead>
<tr>
<th>Rating</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>☐</td>
</tr>
<tr>
<td>1</td>
<td>☐</td>
</tr>
<tr>
<td>2</td>
<td>☐</td>
</tr>
<tr>
<td>3</td>
<td>☐</td>
</tr>
<tr>
<td>4</td>
<td>☐</td>
</tr>
<tr>
<td>5</td>
<td>☐</td>
</tr>
<tr>
<td>6</td>
<td>☐</td>
</tr>
<tr>
<td>7</td>
<td>☐</td>
</tr>
<tr>
<td>8</td>
<td>☐</td>
</tr>
<tr>
<td>9</td>
<td>☐</td>
</tr>
<tr>
<td>10</td>
<td>☐</td>
</tr>
</tbody>
</table>

CURRENT FUNCTION OF YOUR KNEE:

<table>
<thead>
<tr>
<th>Rating</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>☐</td>
</tr>
<tr>
<td>1</td>
<td>☐</td>
</tr>
<tr>
<td>2</td>
<td>☐</td>
</tr>
<tr>
<td>3</td>
<td>☐</td>
</tr>
<tr>
<td>4</td>
<td>☐</td>
</tr>
<tr>
<td>5</td>
<td>☐</td>
</tr>
<tr>
<td>6</td>
<td>☐</td>
</tr>
<tr>
<td>7</td>
<td>☐</td>
</tr>
<tr>
<td>8</td>
<td>☐</td>
</tr>
<tr>
<td>9</td>
<td>☐</td>
</tr>
<tr>
<td>10</td>
<td>☐</td>
</tr>
</tbody>
</table>
Appendix E

Lower Extremity Functional Scale
**Instructions**

We are interested in knowing whether you are having any difficulty at all with the activities listed below because of your lower limb problem for which you are currently seeking attention. Please provide an answer for each activity.

**Today, do you or would you have any difficulty at all with:**

<table>
<thead>
<tr>
<th>Activities</th>
<th>Extreme difficulty or unable to perform activity</th>
<th>Quite a bit of difficulty</th>
<th>Moderate difficulty</th>
<th>A little bit of difficulty</th>
<th>No difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Any of your usual work, housework or school activities.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>2. Your usual hobbies, recreational sporting activities.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>3. Getting into or out of the bath.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4. Walking between rooms.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5. Putting on your shoes or socks.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>6. Squatting.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>7. Lifting an object, like a bag of groceries from the floor.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>8. Performing light activities around your home.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>9. Performing heavy activities around your home.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>10. Getting into or out of a car.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>11. Walking 2 blocks.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>12. Walking a mile.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>13. Going up or down 10 stairs (about 1 flight of stairs).</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>14. Standing for 1 hour.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>15. Sitting for 1 hour.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>16. Running on even ground.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>17. Running on uneven ground.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>18. Making sharp turns while running fast.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>19. Hopping.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>20. Rolling over in bed.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

**Column Totals:** 0 1 2 3 4

---

Page 2

60
Appendix F

Tegner Activity Level Scale

<table>
<thead>
<tr>
<th>Level</th>
<th>Activity Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 10</td>
<td>Competitive sports- soccer, football, rugby (national elite)</td>
</tr>
<tr>
<td>Level 9</td>
<td>Competitive sports- soccer, football, rugby (lower divisions), ice hockey, wrestling, gymnastics, basketball</td>
</tr>
<tr>
<td>Level 8</td>
<td>Competitive sports- racquetball or bandy, squash or badminton, track and field athletics (jumping, etc.), down-hill skiing</td>
</tr>
<tr>
<td>Level 7</td>
<td>Competitive sports- tennis, running, motorcars speedway, handball</td>
</tr>
<tr>
<td></td>
<td>Recreational sports- soccer, football, rugby, bandy, ice hockey, basketball, squash, racquetball, running</td>
</tr>
<tr>
<td>Level 6</td>
<td>Recreational sports- tennis and badminton, handball, racquetball, down-hill skiing, jogging at least 5 times per week</td>
</tr>
<tr>
<td>Level 5</td>
<td>Work- heavy labor (construction, etc.)</td>
</tr>
<tr>
<td></td>
<td>Recreational sports- cycling, cross-country skiing,</td>
</tr>
<tr>
<td></td>
<td>Recreational sports- jogging on uneven ground at least twice weekly</td>
</tr>
<tr>
<td>Level 4</td>
<td>Work- moderately heavy labor (e.g. truck driving, etc.)</td>
</tr>
<tr>
<td>Level 3</td>
<td>Work- light labor (nursing, etc.)</td>
</tr>
<tr>
<td>Level 2</td>
<td>Work- light labor</td>
</tr>
<tr>
<td></td>
<td>Walking on uneven ground possible, but impossible to back pack or hike</td>
</tr>
<tr>
<td>Level 1</td>
<td>Work- sedentary (secretarial, etc.)</td>
</tr>
<tr>
<td>Level 0</td>
<td>Sick leave or disability pension because of knee problems</td>
</tr>
</tbody>
</table>