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Disruptions in Physical and Neurocognitive Wellness after Anterior Cruciate Ligament Reconstruction

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Disruptions in Physical and Neurocognitive Wellness after Anterior Cruciate Ligament Reconstruction
Julie Parkinson Burland, PhD
University of Connecticut, 2019

ABSTRACT: Traumatic knee injuries, such as anterior cruciate ligament (ACL) sprains detrimentally impact long-term health by initiating a cycle of chronic pain, inactivity, and disability. Neural activity alterations have been suggested as a large contributor to numerous aspects of reduced physical function including but not limited to persistent quadriceps strength deficits, aberrant biomechanical movement patterns and reduced self-reported function after ACL reconstruction (ACLR). Emerging evidence strongly points to the notion that psychological deficits also hinder recovery. Notably, neural impairments observed following ACLR may initiate psychological dysfunction, a process defined as learned helplessness (LH). This project will innovatively investigate the constructs of commonly affected after ACLR, including constructs of quadriceps strength, biomechanics, neural activity and psychological function, specifically focusing on establishing LH in this cohort. The central tenet of this work will establish the framework that after ACL injury and ACLR, patients experience alterations in afferent neural drive due to loss of mechanoreception, pain, and swelling, leading to subsequent alterations in central nervous system neural activity. This change in neural activity can either acutely foster an environment of uncontrollability promoting LH or persist, leading to a cyclical pattern of muscle inhibition and weakness, altered joint biomechanics, depressed self-reported and psychological function that generates the construct of LH in these patients; conversely, the change in neural activity can be restored, placing
patients on the path to more positive outcomes. The negative psychological responses that ensue likely can further exacerbate the negative neural responses, creating a cyclical pattern that results in decreased overall quality of life in these patients. A natural extension of our need to comprehensively care for the patient after ACLR is to firstly continue to further understand the relationship between common post-operative outcomes and secondly to more thoroughly consider psychological health during ACL rehabilitation and to recognize LH as a potential barrier to successful recovery. By elucidating these relationships, we can begin to develop future evidence-based interventions capable of promoting both physical and psychological health and improved long-term quality of life.
Disruptions in Physical and Neurocognitive Wellness after Anterior Cruciate Ligament Reconstruction

Julie Parkinson Burland

B.S., University of Connecticut, 2012
M.S., University of Kentucky, 2014

A Dissertation
Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy at the University of Connecticut 2019
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Julie Parkinson Burland

2019
Disruptions in Physical and Neurocognitive Wellness after Anterior Cruciate Ligament Reconstruction

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University of Connecticut
2019
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<th>Full Form</th>
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<tr>
<td>ACL</td>
<td>anterior cruciate ligament</td>
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<tr>
<td>ACLR</td>
<td>anterior cruciate ligament reconstruction</td>
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<tr>
<td>ACL-HI</td>
<td>anterior cruciate ligament helplessness index</td>
</tr>
<tr>
<td>ACL-RSI</td>
<td>anterior cruciate ligament return to sport after injury scale</td>
</tr>
<tr>
<td>ADL</td>
<td>activities of daily living</td>
</tr>
<tr>
<td>AMT</td>
<td>active motor threshold</td>
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<tr>
<td>EMG</td>
<td>electromyography</td>
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<tr>
<td>CAR</td>
<td>central activation ratio</td>
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<tr>
<td>IKDC</td>
<td>international knee documentation committee</td>
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<tr>
<td>KOOS</td>
<td>knee injury and osteoarthritis outcome score</td>
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<tr>
<td>H-reflex</td>
<td>Hoffmann reflex</td>
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<tr>
<td>LHS</td>
<td>learned helplessness scale</td>
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<tr>
<td>MEP</td>
<td>motor evoked potential</td>
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<td>M response</td>
<td>muscle response</td>
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<tr>
<td>MVIC</td>
<td>maximum voluntary isometric contraction</td>
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<tr>
<td>PRO</td>
<td>patient reported outcome</td>
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<tr>
<td>QOL</td>
<td>quality of life</td>
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<tr>
<td>TSK</td>
<td>tampa scale kinesiophobia</td>
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<tr>
<td>tDCS</td>
<td>transcranial direct current stimulation</td>
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CHAPTER 1: INTRODUCTION

1.1 Anterior cruciate ligament (ACL) injuries are debilitating and costly knee injuries affecting upwards of 250,000 individuals annually. While surgical and rehabilitative techniques have made extensive advancements over the last decade, post-operative outcomes are suboptimal, with almost 40% of individuals demonstrating decreased activity levels and reduced quality of life. Restoring quadriceps strength is the primary component of most rehabilitation programs after ACL reconstruction (ACLR). Unfortunately, a significant number of individuals fail to return to pre-injury activity levels, and further those that do return, often present with persistent quadriceps strength deficits and altered biomechanical/neuromuscular movement patterns. As clinicians continue to combat suboptimal postoperative outcomes, lower return to sport rates, and the significant risk for early onset posttraumatic osteoarthritis (PTOA), current ACLR rehabilitation practices need to be re-evaluated to identify areas where modifications can be implemented to provide better comprehensive care.

To date, ACLR rehabilitation strategies largely target restoring quadriceps strength, neuromuscular control and appropriate limb symmetry.
Psychological function also has the capability to directly influence recovery. (Logerstedt, Di Stasi et al. 2014, Ardern and Kvist 2015) Interestingly, psychological dysfunction may be linked with well-known neuromuscular alterations, resulting in a construct termed learned helplessness, and together may perpetuate negative outcomes after ACLR. Emerging evidence suggests that both peripheral and central neural alterations following ACLR may be the driver of many of these persistent consequences and deficits exhibited by patients after ACLR. In order to provide appropriate and comprehensive patient-oriented care, evaluation of the constructs that are affected after ACLR is necessary. Given the mounting evidence supporting the presence and impact of psychological distress after ACLR, and the ability of healthcare clinicians to intervene and optimize psychological function, the purpose of this dissertation is to investigate the constructs and relationships between neural activity, quadriceps strength, biomechanics and self-reported/psychological function and the presence of learned helplessness after ACLR for the purpose of identifying modifiable factors that hinder rehabilitation success.

1.2 Specific Aims

We have conducted a series of investigations that are targeted at evaluating common post-operative outcomes that have direct implications for clinical care after ACLR. It is well established that ACL injury and ACLR negative influence several central constructs such as nervous system activity, quadriceps strength, lower extremity biomechanics, self-reported and psychological function (Figure 1). Current rehabilitation efforts after ACLR are aimed at regaining physical strength and movement control during functional tasks, with the ultimate goal being symmetry between the involved and uninvolved limb. Chapter 3 evaluates the variability and the extent of disagreement
between physical performance measures and lower extremity biomechanics. Previous research has recently indicated that simply evaluating the symmetry between limbs, specifically on functional hop tasks, may in fact overestimate an individual’s physical function. (Wellsandt, Failla et al. 2017) Thus, biomechanical analyses evaluating lower extremity movement patterns can also provide valuable insight into an individual’s physical function after ACLR, as they frequently exhibit altered kinematics and kinetics, which persist despite extensive rehabilitation programs. (Paterno, Schmitt et al. 2010, Oberlander, Bruggemann et al. 2013, Peebles, Renner et al. 2018, Welling, Benjaminse et al. 2018) Aside from physical function, emerging evidence continues to point to reduced patient reported function after ACLR. Patient reported outcomes (PROs) can provide a quantifiable measure of patient status on a variety of domains; however, they do not elucidate the underlying factors contributing to high or low scores in a given domain. In Chapter 4 we examined patient perceived function obtained through clinical patient-reported outcome scales to identify the underlying factors, through qualitative interviews. The intent is to uncover factors that drive an individual’s response on outcomes used after ACLR.

Physical and psychological function are altered after ACLR (Chapter 3 and 4). It is well established that alterations in strength and neural activity are factors that also contribute to rehabilitation failure after ACLR; however, the relationship between these
factors and psychological function are unknown. Neural impairments observed following injury and ACLR may be associated with psychological dysfunction, a phenomenon defined as learned helplessness (LH). In Chapter 5 we have proposed a theoretical framework that establishes the link between depressed neural activity and psychological dysfunction after ACL injury using foundational evidence from neuroscience and psychology to support the integration of LH into recovery. In Chapter 6 to further expand on our previous theoretical hypothesis outlined in Chapter 5, we sought to evaluate if the presence of LH is associated with impairments in neural activity and quadriceps function after ACLR.
CHAPTER 2: REVIEW OF THE LITERATURE

2.1 ANTERIOR CRUCIATE LIGAMENT

ACL injuries are one of the most debilitating knee injuries sustained in athletic populations, affecting nearly 300,000 Americans annually at a cost of nearly $8 billion for surgery and rehabilitative care.(Griffin, Albohm et al. 2006, Mather, Koenig et al. 2013, Hofbauer, Muller et al. 2014) Despite continued advances in surgical and rehabilitative techniques, post-operative outcomes are suboptimal,(Logerstedt, Di Stasi et al. 2014, Ardern 2015) with almost 40% of individuals demonstrating decreased activity compared to preinjury levels(Ardern, Taylor et al. 2014) and reduced quality of life.(Lentz, Zeppieri et al. 2012) Extensive rehabilitative strategies exist to restore quadriceps strength after ACLR; however, a significant number of individuals return to functional activity with quadriceps strength deficits (Figure 1).(Lepley 2015)

Furthermore, individuals who undergo ACLR have an increased risk for long-term complications compared with healthy individuals. Risk of reinjury to the involved limb occurs in at least 5 to 15% of ACLR individuals(Salmon, Russell et al. 2005, Yabroudi, Bjornsson et al. 2016) and the development of

![Deficits at Time of Return to Play (~6 months)](image)
posttraumatic osteoarthritis (PTOA) after ACLR has been reported to occur in approximately 11%, 20% and 52% of individuals within 5, 10 and 20 years, respectively. (Cinque, Dornan et al. 2017) Due to suboptimal postoperative outcomes, lower than expected return to sport rates and the risk for early onset PTOA, there is a need to re-evaluate current ACLR rehabilitation practices and interventions in order to identify areas or components where modifications can be implemented to provide better comprehensive care.

2.2 PURPOSE

The purpose of this review of literature is to detail 1) the function, mechanism of injury and current standard of care of the anterior cruciate ligament (ACL), 2) the global consequences and post-operative outcomes after anterior cruciate ligament reconstruction (ACLR, 3) the relationship between neural alterations and psychological dysfunction, 4) the Learned Helplessness (LH) phenomenon, and 5) promising therapies capable of targeting LH and neural alterations.

2.3 ACL ANATOMY AND FUNCTION

Anatomy

The ACL is a band-like structure composed of dense connective tissues that runs anteriorly, medially and distally from its femoral attachment through the intercondylar notch attaching distally on the tibia. (Amis and Dawkins 1991, Duthon, Barea et al. 2006) The ACL provides both translational and rotatory stability of the knee joint as well as proprioceptive neural input required for appropriate neuromuscular control. (Konishi, Fukubayashi et al. 2002, Krogsgaard, Dyhre-Poulsen et al. 2002) The cross-sectional area of the ACL increases as it runs distally from its proximal femoral attachment to its
insertion on the tibia, with the tibial portion serving as a wider and stronger anchor. Aside from the direct bony attachments to the femur and tibia, the ACL secondarily extends beneath the transverse intermeniscal ligament and into the anterior and posterior horn of the lateral meniscus. (Girgis, Marshall et al. 1975, Arnoczky 1983) The ACL is primarily vascularized by the middle genicular artery, with heavier vascularization located in the proximal aspects of the ligament. A small portion of the ACL receives blood supply through small infrapatellar branches of the inferior genicular arteries; however, there is a zone 5-10 mm proximal to the tibial attachment where there is poor vascularity, promoting poor healing potential of the ACL. (Girgis, Marshall et al. 1975)

Biomechanical Function

As previously mentioned, the ACL plays a critical role in passive knee joint stability, and is a primary restraint of anterior tibial translation relative to the femur in addition to rotary stability. (Butler, Noyes et al. 1980) The ACL consists of three functional bundles which work synergistically to provide mechanical restraint of the knee and include the anteromedial, posterolateral and intermediate bundles; however, the two-bundle model (anteromedial and posterolateral) is most commonly referred to in the literature and is conventionally name based on tibial insertions. (Girgis, Marshall et al. 1975, Amis and Dawkins 1991) The ACL bundles are primarily composed of collagen fascicles that help to provide multidirectional stability, based off of their composition and layout, although the distribution across the bundles varies based on the position of the tibiofemoral joint, muscle contraction and external loads. (Beynnon, Johnson et al. 2005)
The ACL collagen matrix consists largely of Type I collagen fibers that are oriented parallel to the longitudinal axis of the ligament, providing tensile strength. (Duthon, Barea et al. 2006) In specific fibrocartilage regions of the ACL, such as near the tibial and femoral insertions, Types II, III, IV and VI collagen are present, providing additional support in areas of large shear or pressure forces as well as increasing pliability of the ligament, respectively. (Neurath and Stofft 1992) Studies in cadaveric models revealed that the anteromedial aspect of the ACL experiences the highest strain during knee hyperextension and full flexion, while the strain in the posterolateral aspect occurs only during hyperextension. Of clinical importance is the role of strain throughout varying joint angles placed on the ACL by external muscle forces. (Markolf, Gorek et al. 1990, Beynnon, Howe et al. 1992, Smith, Livesay et al. 1993) When near full extension, quadriceps muscle force places strain on the ACL. Additionally, movement from a flexed to extended position, both passively or following muscular contraction, increases strain on the ACL, with the highest in vivo strain values occurring during an isometric contraction of the quadriceps in 15 degrees of knee flexion. (Beynnon, Howe et al. 1992) Therefore, consideration of ACL anatomy and mechanical function is important for reconstructive techniques along with rehabilitative considerations. (Beynnon, Howe et al. 1992, Beynnon, Johnson et al. 2005)

**Neural Function**

The importance of the ACL as a contributor of neural function has been well established. The ACL is mainly innervated from the posterior articular branches of the tibial nerve and is an important vessel for numerous mechanoreceptors that help to provide proprioceptive input to the knee joint during movement. (Zimny, Schutte et al.
Mechanoreceptors of the nerve fibers that innervate the ACL include receptors sensitive to stretch and deformation (Ruffini) along with receptors sensitive (Pacini) to rapid movements and tension (Golgi). These receptors provide the ACL with proprioceptive capability and afferent signaling to the spinal cord and central nervous system for appropriate movement control. Upon deformation or stress to the ligament, afferent nerve endings are activated and trigger contraction of localized muscles surrounding the joint. Free nerve endings located within the ligament, specifically near insertions sites on the femur and tibia, are responsible for transmitting pain signals to the CNS. Involvement of free nerve endings post-injury is important to consider when examining the consequences pain on neural function. The complicated neural components of the ACL are clinically important as input from peripheral nerve endings allows for appropriate neuromuscular control and functional task completion.

2.4 ACL INJURY

Epidemiology

ACL injuries are debilitating and costly, affecting upwards of 300,000 individuals annually, with almost 50% of those individuals falling between the ages of 15-25. Research suggests that ACL injury rates for female athletes are 2 to 8 times higher than male athletes competing in the same sports, at the same level of play. Commonly ACL injuries have been reported to occur in high intensity and skill-
type sports such as those requiring rapid landing strategies, lateral pivoting and quick change in direction type maneuvers, although injury can occur through external contact.

**Etiology**

Contact mechanisms for ACL injury have been reported to occur in 30% of all cases (Griffin, Agel et al. 2000, Joseph, Collins et al. 2013); however, a significant proportion of ACL injuries, upwards of 70%, occur through a non-contact mechanism, and are often the primary focus of injury prevention research and programming. (Joseph, Collins et al. 2013, Kaeding, Leger-St-Jean et al. 2017) Landing and/or plant-cut maneuvers during deceleration or change in direction are frequently reported as sport-related tasks responsible for ACL injury. (Boden, Dean et al. 2000, Hewett, Myer et al. 2005, Cochrane, Lloyd et al. 2007) Typically, deceleration during a jump landing or running while the knee is in shallow flexion, alongside combined motions such as knee valgus and rotations place the knee in a vulnerable position for injury. (Hewett, Myer et al. 2005, Cochrane, Lloyd et al. 2007, Shimokochi and Shultz 2008, Kobayashi, Kanamura et al. 2010, Shultz, Schmitz et al. 2012, Beck, Lawrence et al. 2017) Subsequently risk factors for non-contact ACL injuries and secondary reinjury include poor biomechanical movement patterns in sagittal and frontal planes, (Boden, Dean et al. 2000, Besier, Lloyd et al. 2001) such as increased knee valgus (adduction) (Hewett, Myer et al. 2005), hip adduction (Goerger, Marshall et al. 2015) and reduced hip and knee flexion during landing. (Griffin, Albohm et al. 2006, Kaeding, Leger-St-Jean et al. 2017) Transverse motions at the trunk and hip also have the potential to increase internal rotational forces at the knee (McLean, Huang et al. 2005) and in combination
with altered sagittal and frontal plane movements, highlight the multi-planar nature of non-contact injuries.

The ACL experiences strain when an anteriorly directed force is applied to the tibia, hence serving as a primary restraint to anterior tibiofemoral shear forces. (Woo, Livesay et al. 1992, Sakane, Livesay et al. 1999, Shimokochi and Shultz 2008) When the knee is placed in a more extended position (less than 30 degrees), the ACL experiences tensile loads comparable to that of the external applied shear force. However, tensile forces within the ACL decrease (when the same external load is applied) when the knee is in a more flexed position (greater than 60 degrees). Extensive research has identified that the ACL is placed at a greater risk for injury when the knee is in near extension and experiences excessive anterior loading. (Durselen, Claes et al. 1995, Woo, Fox et al. 1998, Gabriel, Wong et al. 2004, Shimokochi and Shultz 2008)

Aside from positional factors influencing ACL injury risk, external muscle forces, such as those generated by the quadriceps muscles also play a large role in loading the ACL during functional movements. Due to the angle of insertion and the patellar tendon’s direction of pull, the quadriceps muscle group can produce an immense amount of anterior shear force on the tibia, especially during shallow knee flexion. (Pandy and Shelburne 1997, Shelburne, Torry et al. 2005) Unopposed external quadriceps muscle contractions have been theorized to increase the tensile forces placed on the ACL during functional movements and may place an individual at risk for injury. (Nunley, Wright et al. 2003, Shimokochi and Shultz 2008)
2.5 TREATMENT OF ACL INJURY

Treatment Approaches

Both operative and non-operative approaches exist for treatment after ACL injury. A non-operative approach after injury is a viable option for those individuals who report minimal instability and who participate in activities requiring minimal frontal and transverse plane movements, such as cutting and pivoting. (Spindler and Wright 2008) However, surgical reconstruction of the ACL is currently recognized as the leading treatment option after injury for those individuals who experience feelings of instability during activities of daily living or those that wish to continue a high functioning lifestyle, including high intensity sports, recreational activities or hard, manual labor. (Beynnon, Johnson et al. 2005) ACLR primarily aims to restore translational and rotatory stability to the knee joint during functional movements. Secondary benefits of the procedure include the restoration of normal joint kinematics and decreased stresses on the menisci and chondral surfaces. (Beynnon, Johnson et al. 2005, Cinque, Dornan et al. 2017) Unfortunately, regardless of treatment option, 50% of individuals who sustain ACL injury have been shown to develop PTOA within 20 years. (Lohmander, Englund et al. 2007, Luc, Gribble et al. 2014, Cinque, Dornan et al. 2017) Despite continued advances in surgical and rehabilitative techniques, post-operative outcomes are suboptimal. (Logerstedt, Di Stasi et al. 2014, Ardern 2015) with almost 40% of individuals demonstrating decreased activity levels (Ardern, Taylor et al. 2014) and reduced quality of life compared to preinjury levels. (Lentz, Zeppieri et al. 2012) Due to suboptimal postoperative outcomes, lower than expected return to sport rates (Bauer, Feeley et al. 2014, Ardern, Taylor et al. 2015, Dingenen and Gokeler 2017), and the risk
for early onset PTOA, (Keays, Newcombe et al. 2010, Luc, Gribble et al. 2014, Harkey, Luc et al. 2015, Cinque, Dornan et al. 2017) current ACLR rehabilitation practices need to be re-evaluated to identify areas or components where modifications can be implemented to provide better comprehensive care.

_Surgical Techniques_

Over the last several decades there have been numerous advances in surgical techniques and grafting options for ACLR. Although arthroscopically assisted surgical techniques are currently the standard procedure of choice for orthopedic surgeons, tunnel placements, fixations and graft types are highly debated. Both autografts and allografts are used during surgical reconstruction, with autografts, specifically the bone-patellar tendon-bone (BTB) graft and the semitendinosus hamstring (ST) tendon graft or semitendinosus and gracilis tendons (STG), being the most commonly reported and utilized in the literature. (Beynnon, Johnson et al. 2005) There is currently no consensus regarding graft type for ACL reconstruction and is a topic of frequent debate. (Krishnan and Williams 2011) BTB autografts are often the most popular graft choice due to optimal strength characteristics, bone to bone healing and favorable clinical outcomes; however, individuals who opt for BTB autographs have been reported to have higher donor site morbidity and anterior knee pain. (Ejerhed, Kartus et al. 2003, Freedman, D'Amato et al. 2003, West and Harner 2005) Due to bone to bone healing, BTB autografts demonstrate the quickest incorporation and healing with the native bone compared with soft tissue hamstring autografts. (West and Harner 2005) For those individuals participating in high intensity functional activities, lower rates of failure with BTB autografts were noted compared to hamstring tendon autograft (1.9% versus 4.9%,
respectively). (Freedman, D'Amato et al. 2003) However, STG autografts provide satisfactory stiffness and tensile load biomechanical properties, reduced harvest morbidity and favorable patient satisfaction. (West and Harner 2005) There is no consensus in the literature on superior graft choice; ultimately the decision depends on a multitude of factors such as patient activity level, age, tissue availability, existing comorbidities and surgeon/patient preference. (Aglietti, Giron et al. 2004, West and Harner 2005)

2.6 CONSEQUENCES OF ACL INJURY

Physical Consequences

The objectives of ACLR are to provide immediate stabilization and restore adequate joint function as well as preventing long term joint morbidity. (Delay, Smolinski et al. 2001, Beynnon, Johnson et al. 2005, Renstrom 2013) Those who sustain an ACL injury acutely experience immense pain and swelling, (Palmieri-Smith, Villwock et al. 2013) and potentially concomitant joint damage such as meniscal injuries. (Musahl, Jordan et al. 2010, Wilk, Macrina et al. 2012) Notably, in adolescents, a delay in surgical repair has been suggestive of higher likelihood of sustaining articular cartilage damage compared with those who underwent reconstruction immediately. (Newman, Carry et al. 2015) ACL injury and ACLR often result in a decrease physical activity level. (Dunn and Spindler 2010, Spindler, Huston et al. 2011, Ardern, Taylor et al. 2014, Tengman, Brax Olofsson et al. 2014) Secondarily, ubiquitous quadriceps muscle weakness (Palmieri-Smith, Thomas et al. 2008, Lepley 2015), quadriceps atrophy (Williams, Buchanan et al. 2005) and neural alterations (Ingersoll, Grindstaff et al. 2008, Pietrosimone, Lepley et al. 2015, Needle, Lepley et al. 2017) are also
evidenced after ACL injury and ACLR. Joint injury and surgical intervention often results in acute joint effusion and pain. (Pietrosimone, Lepley et al. 2015) Mechanoreceptors native to the ACL are disrupted following injury and reconstruction, thereby relaying altered sensory information to the supraspinal centers and central nervous system, resulting in decreased quadriceps muscle activation, defined as the diminished ability to voluntarily activate optimal number of muscle fibers. Deficits in muscle activation stem from a reduction in alpha motor neuron recruitment and/or firing rate. (Palmieri-Smith, Thomas et al. 2008, Lepley and Palmieri-Smith 2015) Rehabilitation after ACLR heavily focuses on mitigating quadriceps weakness in order to improve these neuromuscular consequences; however, quadriceps weakness and atrophy (a decrease in the size of skeletal muscle) persists well into the chronic phases of recovery. (Keays, Bullock-Saxton et al. 2001, Lewek, Rudolph et al. 2002, Becker, Berth et al. 2004, Lautamies, Harilainen et al. 2008, Palmieri-Smith, Thomas et al. 2008, Eitzen, Holm et al. 2009, Lepley 2015, Otzel, Chow et al. 2015) Individuals who undergo ACLR also have an increased risk for long term complications compared with healthy individuals. Risk of reinjury to the involved limb occurs in at least 5 to 15% of ACLR individuals (Salmon, Russell et al. 2005, Yabroudi, Bjornsson et al. 2016) and the development of PTOA after ACLR has been reported to occur in approximately 11%, 20% and 52% of individuals within 5, 10 and 20 years, respectively. (Cinque, Dornan et al. 2017) Individuals sustaining ACL injury comprise about 25% of the total population with knee OA. (Brown, Johnston et al. 2006) In male and female soccer players sustaining ACL tears, about 80% had radiographic PTOA 12-14 years later, regardless of surgical intervention and further, 70% had functional limitations and reduced quality...
of life. The peak incidence of ACL injury is 16 years of age, creating significant long-term health and economic burden. (Roos, Roos et al. 1998, Rincon, Vyas et al. 2011, Neogi 2013, Luc, Gribble et al. 2014)

**Psychological Consequences**


However, rising awareness in the literature has identified psychological function as a critical component to rehabilitative success, which is often overlooked. (Logerstedt, Di Stasi et al. 2014, Ardern and Kvist 2015) Previous work supports the notion that an individual’s decision to return to sport after injury is largely influenced by modifiable psychological factors such as hesitancy, kinesiophobia, lack of confidence, or fear of re-injury. (Langford, Webster et al. 2009, Tjong, Murnaghan et al. 2014, Ardern 2015, Burland, Toonstra et al. 2018) These components may act as barriers to successful rehabilitative outcomes and reintegration into sports. (Tjong, Murnaghan et al. 2014, Burland, Toonstra et al. 2018) Specific to the knee, psychological factors related to kinesiophobia, fear of re-injury or decreased self-efficacy are directly related to self-reported knee function and readiness to return to play. (Flanigan, Everhart et al. 2013, Hart, Collins et al. 2014) Early data also indicate that psychological distress after injury, referred to as Learned Helplessness (LH), may also be linked to neurological dysfunction, which is a well-known complication of ACL injury, further justifying the need
to consider psychological health during ACL rehabilitation. (Maier 1976, Taub, Uswatte et al. 2006) Though the root and contributions of psychological distress are not yet fully understood, emerging evidence does suggest that psychological factors play a large role in rehabilitative success.

2.7 POST-OPERATIVE OUTCOMES

There are numerous established consequences that occur after ACLR. Clinically many of these outcomes manifest as quadriceps weakness. Additionally, despite extensive focus on restoring quadriceps strength after ACLR, many patients continue to exhibit diminished strength and neural consequences originating from the quadriceps musculature that should be taken into consideration throughout recovery. This section will outline both the clinical and neural implications of ACLR.

2.8 QUADRICEPS WEAKNESS

Functional stability of the knee joint is facilitated through dynamic contractions of the surrounding musculature, primarily the muscles of the quadriceps femoris group. (Keays, Bullock-Saxton et al. 2003, Roberts, Ageberg et al. 2007, Palmieri-Smith, Thomas et al. 2008) Quadriceps muscle activation, has been highly correlated with functional stability, increasing knee stiffness by 48%. (Keays, Bullock-Saxton et al. 2001, Keays, Bullock-Saxton et al. 2003) Naturally, quadriceps strengthening is a main component of most rehabilitative programs after ACLR; however, despite extensive rehabilitative strategies aimed at optimizing quadriceps function, persistent quadriceps weakness has been recognized as a common consequence that is still present during the chronic phases of recovery. (Ingersoll, Grindstaff et al. 2008, Palmieri-Smith, Thomas et al. 2008, Lepley, Gribble et al. 2015) Although presence of quadriceps

2.9 QUADRICEPS INHIBITION

Inhibition, or the inability to fully contract uninjured musculature surrounding an injured joint, is a reflexive mechanism reported following traumatic joint injury and plays a major role in acute quadriceps activation deficits evidenced immediately following ACL surgery. (Hopkins and Ingersoll 2000, Hart, Pietrosimone et al. 2010) Despite no direct injury to the muscle fibers or innervating nerve, patients demonstrate significant difficulty in initiating and sustaining a full quadriceps contraction. Although inhibition has been previously suggested as an initially protective mechanism, prolonged quadriceps inhibition may lead to decreased joint health. (Becker, Berth et al. 2004) Previous research suggests that peripheral disruption of mechanoreceptors in the ACL, with or
without concomitant joint swelling and pain, can cause abnormal afferent signaling to the spinal cord and supra-spinal centers, leading to a diminished alpha motor neuron input to the quadriceps muscles. (Young, Stokes et al. 1987, Palmieri, Tom et al. 2004, Palmieri-Smith, Thomas et al. 2008, Hart, Pietrosimone et al. 2010, Pietrosimone, McLeod et al. 2012, Palmieri-Smith, Villwock et al. 2013) Loss of appropriate afferent signaling decreases the ability to actively recruit high threshold motor units during voluntary contractions, often termed quadriceps activation failure. Quadriceps inhibition has been established as an inability to voluntarily recruit maximal numbers of motor units and the extent to which they can maximize firing frequency, thereby generating submaximal force. (Palmieri-Smith and Thomas 2009, Hart, Pietrosimone et al. 2010, Harkey, Luc-Harkey et al. 2016) Quadriceps inhibition has been universally described in ACL-deficient limbs and in patients who have undergone ACLR. (Palmieri-Smith, Thomas et al. 2008, Hart, Pietrosimone et al. 2010, Lepley and Palmieri-Smith 2015) Quadriceps inhibition not only influences the ACLR limb, but has been shown to occur to the “healthy”, contralateral limb, demonstrating the clinical need to address the root of quadriceps inhibition to combat weakness.

2.10 PERIPHERAL MECHANISMS OF QUADRICEPS INHIBITION

Several factors that alter joint afferent activity have been identified as potential contributors to quadriceps inhibition and weakness after joint injury. Three peripheral contributors are outlined in the subsequent paragraphs.

Swelling

After traumatic joint injuries, such as with ACL sprains, there is evidence of acute intraarticular joint swelling that has been linked with significant quadriceps inhibition.
Studies investigating experimental models of effusion with fluid injection levels varying from as little as 10mL to upwards of 55 mL have demonstrated significant quadriceps inhibition. (Young, Stokes et al. 1987, Palmieri, Tom et al. 2004, Palmieri-Smith, Kreinbrink et al. 2007, Palmieri-Smith, Villwock et al. 2013) Prolonged effusion in an ACL population is not uncommon and presents as a clinical pitfall. Individuals who chronically present with relatively small effusions (<10mL), often not detectable by simple visual observation demonstrate the inability to optimally activate the quadriceps muscles. (Young, Stokes et al. 1987) Pathological and experimental model findings demonstrate that following a rise in joint intra-articular pressure, there is an altering in the firing rate and recruitment of Group II afferent fibers which leads to an inhibitory effect on the quadriceps muscle. Quadriceps inhibition as a consequence of simulated knee joint effusion has been evidenced to alter electromyography (EMG) patterns (Stratford 1982, Torry, Decker et al. 2000) decrease quadriceps strength (Jensen and Graf 1993, McNair, Marshall et al. 1996) and alter appropriate recruitment of motorneurons. Motorneuron recruitment is often measured using the Hoffmann reflex. (Hopkins and Ingersoll 2000, Hopkins, Ingersoll et al. 2001, Hopkins 2006)

**Pain**

Pain, alongside swelling, has been identified as a peripheral contributor in quadriceps inhibition. (Palmieri-Smith, Villwock et al. 2013) Originally proposed as a protective immobilization mechanism for the joint after injury, pain works to decrease quadriceps activation through increasing afferent discharge of free nerve endings (responsible for pain signals) in turn increasing the pain signaling to the central nervous system (CNS). Reduction of quadriceps inhibition (measured through quadriceps
activation) following experimental knee effusion has been evidenced after intra-articular injection of local anesthetics,(Deandrade, Grant et al. 1965, Young, Stokes et al. 1987, Young 1993) however the overall relationship between pain and quadriceps inhibition is inconsistent in the literature, as numerous experimental knee effusion models have demonstrated the presence of quadriceps inhibition in the absence of pain.(Hopkins and Ingersoll 2000, Hopkins, Ingersoll et al. 2001, Palmieri, Tom et al. 2004, Torry, Decker et al. 2005, Hopkins 2006, Palmieri-Smith, Kreinbrink et al. 2007)

**Damaged Joint Receptors**

As previously stated, mechanoreceptors native to the ACL ligament provides somatosensory and stabilizing muscular reflexes to the knee joint.(Grigg and Greenspan 1977, Lephart, Pincivero et al. 1997, Georgoulis, Pappa et al. 2001) After injury to the ACL, there is a disruption in the sensory receptors that innervate the ligament, causing a relay of altered afferent information to the spinal cord and CNS.(Young 1993) This type of altered sensory and proprioceptive input has the potential to contribute to quadriceps muscle inhibition.(Georgoulis, Pappa et al. 2001, Ochi, Iwasa et al. 2002) Ultimately there is a reduced somatosensory function of the ligament after injury, leading to disruption of afferent signaling, presenting clinically as quadriceps inhibition. (Deandrade, Grant et al. 1965)

### 2.11 CENTRAL MECHANISMS TO QUADRICEPS INHIBITION

A normally functioning CNS modulates afferent input received from the periphery; however, after injury the CNS has been thought to significantly reduce alpha motor neuron pool excitability, resulting in quadriceps inhibition and dysfunction. The
mechanisms outlined in this section are proposed mechanisms responsible for quadriceps inhibition originating from the CNS.

**Pre-synaptic Inhibition**

Quadriceps inhibition may in part be due to pre-synaptic inhibition where inhibitory interneurons prevent the release of specialized neurotransmitters required for eliciting appropriate quadriceps contractions. Although the exact mechanism behind pre-synaptic inhibition is unknown, studies examining experimental knee effusion models have demonstrated the presence of pre-synaptic inhibition. (Jones, Jones et al. 1987, Iles, Stokes et al. 1990, Palmieri, Weltman et al. 2005) Specifically, pre-synaptic inhibition is thought to occur due to inhibitory interneurons (gamma-aminobutyric acid (GABA) neurotransmitters) reducing the amplitude of pre-synaptic action potentials, ultimately preventing the release of neurotransmitters required for appropriate quadriceps contraction. (Meunier and Pierrot-Deseilligny 1998, Palmieri, Weltman et al. 2005)

**Reciprocal Inhibition**

Reciprocal inhibition is mechanism of inhibition where Ia afferent fibers arising from the homonymous muscle, simultaneously cause the agonist muscle to contract, subsequently inhibiting the antagonist muscle. Although no direct evidence of reciprocal inhibition after knee injury currently exists, reciprocal inhibition has been identified in a cohort of individuals with chronic ankle instability (CAI). Specifically, bilateral inhibition of the hamstring musculature and facilitation of the quadriceps ipsilateral to the involved limb were present in those with CAI. (Sedory, McVey et al. 2007) Additional research regarding the effect of reciprocal inhibition on the knee joint is warranted.
**Recurrent Inhibition**

Recurrent inhibition (a post-synaptic mechanism) is a process that is mediated by overactive Renshaw cells. Renshaw cells function to regulate alpha motoneuron activity by innervating and inhibiting the same alpha motoneuron that caused it to fire. In addition to inhibiting alpha motoneuron neurons, Renshaw cells also establish connections with gamma motoneurons and Ia inhibitory interneurons and also receive input from descending pathways. (Ellaway 1971, Ellaway and Murphy 1981, Appelberg, Hulliger et al. 1983, Noth 1983, Palmieri, Tom et al. 2004) Importantly knee effusion models have demonstrated the occurrence of recurrent inhibition in the quadriceps musculature. (Spencer, Hayes et al. 1984, Iles, Stokes et al. 1990, Palmieri, Tom et al. 2004) Recurrent inhibition of alpha motoneurons is described as a gating mechanism, reducing the sensitivity of alpha motoneurons to alterations in efferent signaling, subsequently leading to quadriceps inhibition. (Palmieri, Tom et al. 2004)

**Non-Reciprocal inhibition**

Non-reciprocal inhibition is another inhibitory process that may play a role in quadriceps inhibition. Non-reciprocal inhibition is a neural mechanism where Ib afferent interneurons receive excitatory input from the Golgi tendon organs. The Ib afferent fiber originating from the muscle bifurcates in the spinal cord where one branch of the fiber inhibits the homonymous muscle and the other facilitates the antagonist muscle. Subsequently, this causes inhibition of the homonymous muscle and the antagonist is able to contract. Evidentiary support for non-reciprocal inhibition has been demonstrated in a clinical knee effusion model where authors observed depressed neural activity of the quadriceps muscle. (Iles, Stokes et al. 1990)
**Gamma Loop Dysfunction**

Gamma loop dysfunction occurs when there is abnormal gamma motorneuron function. Abnormal function of the gamma motorneurons and decrease in efferent signaling results in a reduction in the baseline activity of alpha motorneurons. Researchers have proposed that joint afferent mechanoreceptors have the ability to indirectly influence alpha motor output, through the gamma loop. (Johansson, Sjolander et al. 1990, Konishi, Fukubayashi et al. 2002) The gamma loop is a spinal-reflex arc where gamma motorneurons (fusimotorneurons) innervate fibers within the muscle primary spindles. (MacIntosh, Gardinier et al. 2006) Subsequently the loss of excitatory input from the primary muscle spindles and joint afferents, alters gamma motorneuron signaling and ultimately reduces alpha motorneuron excitability, leading to muscle inhibition.

**2.12 QUADRICEPS ATROPHY**

Much of the literature on quadriceps weakness and decreased voluntary activation have theorized that altered motor unit recruitment presumably results in quadriceps atrophy (decrease in size of skeletal muscle) although the actual origin is still unknown. (Young, Stokes et al. 1987, Urbach, Nebelung et al. 1999, Williams, Buchanan et al. 2005, Palmieri-Smith, Thomas et al. 2008) Disuse atrophy, such as occurring through immobilization after surgery, detraining and/or decreased physical activity of the involved limb (largely due to rehabilitation contraindications) have previously been suggested to contribute to quadriceps weakness after ACLR. (Palmieri-Smith, Thomas et al. 2008) However, numerous authors suggest that the ubiquitous quadriceps weakness evidenced after ACLR is the result of both atrophy and
manifestations of incomplete volitional muscle activation and impairments in neural function. (Snyder-Mackler, De Luca et al. 1994, Palmieri-Smith, Thomas et al. 2008, Thomas, Wojtys et al. 2016) Previous reports have shown that quadriceps atrophy and activation failure together explain 62% of the variance in quadriceps weakness after ACL injury. (Williams, Buchanan et al. 2005) Additionally, quadriceps inhibition upwards of 15% and 16% (Urbach, Nebelung et al. 1999) in both reconstructed and contralateral limbs has been observed in ACLR individuals 2 years post-operatively. However, preliminary data from our lab is demonstrating that varying neural alterations have the potential to influence quadriceps strength and post-operative function differently throughout recovery. Likewise, there has been a marked increase in literature that points to different drivers of quadriceps weakness during various stages after traumatic knee injuries. Patients who were one month removed from total knee arthroplasty exhibited significant quadriceps weakness, inhibition and decrease in muscle cross-sectional area. Acutely, authors determined that the marked quadriceps strength loss (approximately 62% strength loss) was largely due to quadriceps inhibition and atrophy. (Mizner, Petterson et al. 2005)

Over the course of recovery, improvement in quadriceps inhibition is expected, with a long-term follow-up study after total knee arthroplasty reporting improvements in quadriceps activation from 76% pre-operatively to 85% around 3 years post-operatively. (Berth, Urbach et al. 2002) Notably, an additional study observed that in a chronic ACLR cohort between 2 and 15 years post-operatively, persistent strength deficits were largely related to peripheral changes in the musculotendinous units of the quadriceps muscle, including chronic atrophy and alterations in muscle architectural
arrangement and composition, rather than from quadriceps inhibition. (Krishnan and Williams 2011) Similarly, Noehren et al reported alterations in quadriceps musculature, stemming from reductions in muscle fiber volume and pennation angle, and subsequently smaller quadriceps muscle cross-sectional area, despite those individuals undergoing ACLR and lengthy rehabilitation. (Noehren, Andersen et al. 2016) Recent innovative data also demonstrates that after ACLR, independent of alpha motorneuron activation, there is a reduction in the force generating capacity of individual muscle fibers. (Gumucio, Sugg et al. 2018) Together these data demonstrate that variability in neural alterations, atrophy and muscle physiology likely play an important role in driving quadriceps weakness at different times throughout recovery.

2.13 QUADRICEPS NEURAL ALTERATIONS

Spinal-Reflexive Excitability

Alterations in spinal-reflexive excitability have also been observed acutely after ACL injury and following ACLR. (Pietrosimone, Lepley et al. 2015) Spinal-reflexive excitability can be affected by factors such as joint effusion, pain and descending supraspinal input. (Rosenthal, Moore et al. 2009) Specifically, studies have reported that following artificial knee joint effusion, quadriceps function was adversely affected through inhibition of spinal-reflexive excitability. (Hopkins and Ingersoll 2000, Palmieri, Tom et al. 2004, Rosenthal, Moore et al. 2009) Quadriceps Hoffmann reflex (H-reflex) is used to
assess neuromuscular excitability and is an estimate of the motorneuron pool that can be activated reflexively. (Rosenthal, Moore et al. 2009, Hart, Pietrosimone et al. 2010) Clinical evidence has shown that prior to and acutely after ACLR, individuals who had sustained an ACL injury exhibited depressed spinal-reflexive excitability compared with healthy matched controls. (Lepley, Gribble et al. 2015) Additionally, once patients progressed past the acute stages after surgery, where swelling and pain symptoms normally decline, increases in spinal-reflexive excitability were noted. (Ingersoll, Grindstaff et al. 2008, Palmieri-Smith and Thomas 2009, Rosenthal, Moore et al. 2009, Lepley, Gribble et al. 2015) Although reflexive alterations are evident acutely after ACL injury and surgery, as well as in clinical models of effusion, these reflexive deficits have not been observed to date in the chronic phases of injury. Individuals who were 6 months, 2 years or 4 years removed from ACLR demonstrated minimal alterations in reflexive excitability. (Kuenze, Hertel et al. 2015, Lepley, Gribble et al. 2015, Pietrosimone, Lepley et al. 2015)

**Corticospinal Excitability**

Depressed neural activity, (Lohmander, Englund et al. 2007) specifically brain mediated primary motor cortex (corticospinal) excitability, has been identified as a chronic consequence after ACLR and a proposed mechanism behind persistent quadriceps weakness (Heroux and Tremblay 2006, Norte, Pietrosimone et al. 2010, Pietrosimone, Lepley et al. 2013, Lepley, Ericksen et al. 2014, Lepley, Bahlur et al. 2015)(Figure 2). Alterations to the primary motor cortex and depressed excitability of descending motor pathways after injury are commonly evaluated using transcranial magnetic stimulation (TMS). (Norte, Pietrosimone et al. 2010, Groppa, Oliviero et al.
By eliciting an isolated magnetic stimulus to the brain (motor cortex area), corresponding muscle responses can be examined and primary motor cortex function can be assessed. Various methods for evaluating corticospinal excitability include active motor thresholds (AMT), which assess the threshold required for descending pyramidal neurons to depolarize, (Groppa, Oliviero et al. 2012, Needle, Lepley et al. 2017) as well as motor evoked potentials (MEPs), a measure of the stimulus magnitude capable of being transmitted through descending motor pathways. (Needle, Lepley et al. 2017) (Heroux and Tremblay 2006, Norte, Pietrosimone et al. 2010, Pietrosimone, Lepley et al. 2013, Lepley, Ericksen et al. 2014, Lepley, Bahhur et al. 2015) Existing literature demonstrates that when compared to healthy controls, individuals who were on average 2 years removed from ACLR exhibited larger alterations in neural activity, specifically depressed corticospinal excitability. (Lepley, Ericksen et al. 2014, Pietrosimone, Lepley et al. 2015) In contrast however, individuals who were more acutely removed from ACLR (~70 days) did not exhibit differences in corticospinal excitability compared to healthy controls, demonstrating the potential chronicity of corticospinal alterations. (Ward, Pearce et al. 2016) Emerging hypotheses regarding the underlying contributor to long term alterations in corticospinal excitability have suggested that cortical reorganization and brain neuroplasticity, following altered peripheral input, may be responsible for the persistent and chronic motor impairments seen years after ACLR. (Maier 1976, Taub, Uswatte et al. 2006, Ward, Pearce et al. 2015, Needle, Lepley et al. 2017, Smallheer, Vollman et al. 2017)
2.14 CLINICAL BIOMECHANICAL CONSIDERATIONS

Quadriceps strength deficits have been suggested to persist for years following ACLR; potentially contributing to long term aberrant knee biomechanics, decreased force attenuation, altered limb loading and increased risk of reinjury. (Palmieri-Smith and Thomas 2009, Thomas, Lepley et al. 2015) New evidentiary support of altered force attenuation and loading patterns after ACLR demonstrated that during both single and double limb landing tasks, individuals who had undergone ACLR exhibited significant reductions in the ACL limb knee extension moments and vertical ground reaction forces. (Lepley and Kuenze 2018) These findings highlight the potential unloading of the injured limb after ACLR, despite rehabilitation efforts to restore biomechanical function to pre-surgery levels, raising awareness of the potential implications for reinjury and development of PTOA. (Lepley and Kuenze 2018) Alterations in neuromuscular function, stemming from depressed neural activity and reduced quadriceps strength, exacerbate poor landing and movement mechanics (i.e. reduced knee flexion angles and knee moments) and often persist for months to years after ACLR. (Pietrosimone, McLeod et al. 2012, Thomas, Lepley et al. 2015) Altered sagittal plane gait characteristics between 6 and 12 months after ACLR demonstrate that individuals walk with lower knee flexion angles and extension moments compared to contralateral knees and healthy controls. (Hart, Culvenor et al. 2016) Appropriate quadriceps strength is required for proper force absorption and joint loading; unfortunately, many individuals return to physical activity with large quadriceps strength deficits and alterations in quadriceps activation (neural impairment) and lower extremity biomechanics. (Lewek, Rudolph et al. 2002) Decreased knee flexion angles and extensor moments (Lewek, Rudolph et al. 2002)
2002, Lepley, Wojtys et al. 2015) support the notion that altered quadriceps activation patterns and neuromuscular control may be a chronic consequence of depressed neural excitability after ACLR. Alternatively, a recent study investigating quadriceps neuromuscular function and sagittal-plan knee biomechanics demonstrated that greater quadriceps strength (measured using MVIC) was associated with greater peak-knee flexion angle and less vertical ground reaction force during a jump-landing task. (Ward, Blackburn et al. 2018) Additionally, less quadriceps inhibition (CAR) was associated with greater peak internal knee extension moment, highlighting the importance of quadriceps strength for proper force attenuation during functional movements. Such negative cyclical relationships require further investigation in order to prevent continued dysfunction and long-term joint degeneration.

2.15 PSYCHOLOGICAL DYSFUNCTION AFTER ACL INJURY

Following ACL injury and ACLR, psychological dysfunction is common and often plays a large role in an individual's decision to resume sport related activities. (Gobbi and Francisco 2006, Ardern and Kvist 2015, Bien and Dubuque 2015, Dingenen and Gokeler 2017, Burland, Toonstra et al. 2018) More importantly, psychological dysfunction that goes unaddressed has the potential, in conjunction with other suboptimal physical outcomes, to promote increased disability. (Kvist, Ek et al. 2005, Pietrosimone, Lepley et al. 2013, Christino, Fantry et al. 2015, Lentz, Zeppieri et al. 2015, Lepley 2015) In order to comprehensively provide effective treatment for individuals who undergo ACLR, recognizing and understanding the consequences of prolonged psychological dysfunction (notably the presence of LH) on recovery is essential.
Established Psychological Barriers after ACLR

Psychological factors experienced by athletes after major joint injury may include anger, anxiety, depression, (Morrey, Stuart et al. 1999) fear of reinjury, kinesiophobia, lack of self-efficacy or confidence. (Wiese-Bjornstal, Smith et al. 1998, Everhart, Best et al. 2013, Ardern and Kvist 2015) Importantly, there is a growing body of evidence to suggest that these psychological factors are central to recovery and have the capability to be modified appropriately to influence rehabilitative success and return to play. (Ardern 2015) Recent systematic reviews have demonstrated that more positive psychological responses (i.e. confidence, self-efficacy, optimism, increased motivation, lower fear) increase the likelihood of returning to play. (Everhart, Best et al. 2013, Feller and Webster 2013, te Wierike, van der Sluis et al. 2013) Though psychological dysfunction is known to influence post-operative outcomes, the root of psychological factors such as fear of reinjury, lack of self-efficacy or confidence, are not well understood and largely differ from person to person. It is likely that individual variations in psychological responses are a consequence of differing appraisals and perceptions of injury and of their physical capability. (Ardern 2015) In fact, those who feel they will not be successful in completing a specific task or at returning to preinjury sport may demonstrate self-limiting tendencies. (Podlog and Eklund 2005, Ardern 2015, Burland, Toonstra et al. 2018) Conversely, literature also demonstrates a consistent relationship between higher levels of self-confidence, optimism and motivation and successful return to sport following ACLR. (Gobbi and Francisco 2006, Everhart, Best et al. 2013) Recognition of these psychological characteristics has clinical implications as it can identify areas where targeted interventions can be implemented to mitigate poor
outcomes. Specifically, several qualitative studies have identified common themes experienced amongst individuals who undergo ACLR, reporting that a majority of individuals report feelings of fear, hesitation or kinesiophobia upon return to sport. (Tjong, Murnaghan et al. 2014, Burland, Toonstra et al. 2018) Fear of reinjury or fear of movement are thought to arise from associating certain movements with pain or subsequent injury and are common responses throughout the recovery after ACLR. (Chmielewski, Jones et al. 2008, Wiese-Bjornstal 2010, Flanagan, Everhart et al. 2013, te Wierike, van der Sluis et al. 2013) In fact, fear of reinjury alone has been cited as one of the primary factors for not returning to pre-injury sport with a recent systematic review indicating that individuals who demonstrate lower fear of reinjury have a higher likelihood of returning to preinjury level. (Ardern 2015) Athletes also commonly report feelings of fear related to sport and skill performance. Such emotions prior to returning to sport have been suggested to stem from a potential lack of confidence in the capability to perform at their preinjury skill level. In many cases, these emotions of anxiety or hesitation to utilize the involved extremity may be due to expectations of failure or lack of confidence and may initiate adoption of poor lower extremity movement patterns. (Kvist, Ek et al. 2005) Other psychological factors such as self-efficacy, an individual’s perception of their capability in completing a task, also play a role in success of a rehabilitation outcomes after ACLR. (Thomeé, Währborg et al. 2007, Heijne, Axelsson et al. 2008, Brand and Nyland 2009, Chmielewski, Zeppieri et al. 2011, te Wierike, van der Sluis et al. 2013) Higher levels of self-efficacy may increase the athlete’s motivation and drive. Subsequently, athletes who report higher levels of self-efficacy have a greater likelihood of returning to sport following
ACLR (Thomeé, Währborg et al. 2007, Brand and Nyland 2009) and improved physical activity and knee symptoms/function one year following ACLR. (Thomeé, Währborg et al. 2008, te Wierike, van der Sluis et al. 2013)

Unconventional Psychological Factors Potentiating Dysfunction after ACLR

Alongside the well-established, aforementioned psychological barriers evidenced after ACLR, additional models of psychological dysfunction after traumatic injury have been illustrated in the sport psychology literature. Exposure to uncontrollable outcomes, often termed “uncontrollability” has been cited as a large culprit of psychological distress and may be important with regards to successful outcomes. Specifically, health locus of control describes the belief that one’s health status is controlled by either their own behaviors or by outside factors, such as fate. (Wallston, Wallston et al. 1978) Conventionally, individuals who perceive events to be a consequence of their actions, rather than an event occurring due to fate or chance have reported improved knee satisfaction, both in activities of daily living and in sports activities. (Podlog and Eklund 2006, Podlog and Eklund 2010, te Wierike, van der Sluis et al. 2013) Consequently, the learned helplessness paradigm is based on a theoretical model of uncontrollability, where LH is evident in individuals who believe that their ability to achieve a specific task is not within their control. Because LH is often referred to as a maladaptive trait in response to uncontrollability, it may be an important psychological component to bear in mind when examining physical and psychological outcomes after ACLR.

Although physical and psychological readiness to return to sport may not coincide during recovery, (Gobbi and Francisco 2006, Everhart, Best et al. 2013, Ardern 2015) it is likely that physical and psychological factors are interrelated and play a role
in successful recovery following ACLR. Acknowledgement of both the common and unconventional psychological factors that may arise after ACLR and how they play a role in influencing rehabilitative success is critical for clinicians who hope to optimize post-operative function and promote improved quality of life.

2.16 LEARNED HELPLESSNESS

History of LH Hypothesis

LH is a motor deficit consequence of injury, resulting in impaired motor “escape” behaviors, reduced motivation, and psychological deficits. (Klein, Fencil-Morse et al. 1976, Maier 1976, Samwel, Evers et al. 2006, Taub, Uswatte et al. 2006, Salomons, Moayedi et al. 2012) Such motor deficits have been proposed to originate not from the injury itself, but from a learned suppression of movement. (Taub, Uswatte et al. 2006, Salomons, Moayedi et al. 2012) The LH phenomenon suggests that in response to uncontrollable stress (i.e. traumatic injury), individuals experience increased stress responses and deficits in learning and motivation. Individuals who exhibit helplessness perceive that their responses or actions towards a task or outcome are ineffective, leading them to adopt negative movement strategies. (Klein, Fencil-Morse et al. 1976, Taub, Uswatte et al. 2006) LH has been well demonstrated in both animal and chronic disease literature; where central alterations in neural activity coincide with depressed psychological function and perception of ability to succeed in specific tasks. (Taub, Uswatte et al. 2006, Salomons, Moayedi et al. 2012, Kim, Perova et al. 2016)

The phenomenon of learned helplessness was originally proposed in 1967 by Seligman and Maier (Maier 1976) who theorized that animals learned that outcomes were independent of their responses and that nothing they did mitigated and/or
improved their situation. In these experiments, this LH phenomenon was the root of their failure to escape an aversive stimulus. They described the phenomenon using three different scenarios. (Maier 1976) Initially they developed an experiment where naïve dogs and naïve rats were placed in a shuttle box and encouraged to cross a barrier using a series of electrical stimuli. Once the barrier was crossed, no additional electrical stimuli were given. This first group of naïve dogs were the control group and demonstrated a positive learning response to the stimuli. Next, a separate cohort of animals was placed in the shuttle box but these animals were not given the ability to “escape”. In this cohort, the animals received repeated stimuli. Consequently, these animals developed submissive behavior, they laid down, no longer trying to escape the stimulus. Similarly, in a subsequent experiment to the aforementioned research, Seligman and Maier demonstrated similar responses in college students who were given a series of 25 letter anagrams. The first scenario involved a college student solving 25 letter anagrams with the same repeating pattern. Once the anagram was solved, the student was able to discern the pattern and easily solved the remaining anagrams. This outcome was in striking contrast to the second college student who was initially exposed to a variety of solvable and unsolvable anagrams, amidst a series of loud, inescapable tones. The second college student was unable to solve several of the initial anagrams, exceeding the time allotted (100 sec) for solving them. Because this student was initially exposed to aversive stimuli that were inescapable, when faced with an anagram that was solvable, the student demonstrated difficulty and frustration and solved the puzzle much less efficiently than the first college student.
Following the conclusion of their experiments, Seligman and Maier proposed that LH could be described by the reaction to “uncontrollability”. Specifically, an individual has the potential to learn that their behavior is independent of the outcome and this type of learning produces motivation, cognitive and emotional deficits. (Maier 1976) In 2016, Seligman and Maier published an updated version of their LH theory stating that their original theory was backwards. They state that passivity in response to aversive stimuli is not learned but that it is the default, unlearned response to prolonged aversive events, ultimately inhibiting escape. (Maier and Seligman 2016) Seligman and Maier suggest that passivity as seen in their original experiments can be overcome by learning control, such that animals or humans learn that they can control aversive events.

**Evidence of LH in Animal Models and Human Conditions**

Similar to the classic experiments developed by Seligman and Maier, Taub et al. (Taub, Uswatte et al. 2006) developed a similar theory of limb learned nonuse following deafferentation (sensation surgically removed) of monkeys. Following deafferentation, monkeys would avoid using the injured limb (learned nonuse) even though they possessed the sufficient motor innervation to do so. Attempted use of the deafferented limb caused failure of task completion and aversive events (i.e. falling, dropping food etc.) Similarly, it has been proposed by others that human individuals who are exposed to stressful, uncontrollable situations or chronic disease demonstrate a learned inability to successfully complete a task or feel that the outcome of the situation is out of their control. (Klein, Fencil-Morse et al. 1976, Salomons, Moayedi et al. 2012, Smallheer, Vollman et al. 2017) Similarly, in humans, individuals who are exposed to stressful, uncontrollable situations or chronic disease demonstrate a learned
inability to successfully complete a task or feel that the outcome of the situation is out of their control. (Klein, Fencil-Morse et al. 1976, Salomons, Moayedi et al. 2012, Smallheer, Vollman et al. 2017) Conditions often resulting in LH include stroke, multiple sclerosis, Parkinson’s, arthritis and myocardial infarction. (Shnek, Foley et al. 1997, Samwel, Evers et al. 2006, Johnson, Paranjape et al. 2011, Salomons, Moayedi et al. 2012, Jia and Jackson 2016, Smallheer, Vollman et al. 2017)

2.17 SUMMARY OF LITERATURE REVIEW

Traumatic knee injuries, such as anterior cruciate ligament (ACL) sprains, have detrimental effects on long-term health as they initiate a cycle of chronic pain, physical inactivity, and disability. Alterations in strength and neural activity are potential factors leading to rehabilitation failure after ACL reconstruction (ACLR); however, psychological deficits also hinder rehabilitative success and the root of these deficits is unknown. Neural impairments observed following ACLR may initiate psychological dysfunction, a process defined as learned helplessness (LH). Contributions of psychological dysfunction and psychological barriers (including LH) are likely linked to physical capability and function after ACLR, potentially through neurological mechanisms. Although there is an established evidence-base indicating an association between nerve injury and psychological dysfunction in other models of disease and injury, to date, there is no research to support the link between depressed neural activity and psychological dysfunction after ACL injury. As such, the best approach to understanding this relationship in an ACLR population will come from using foundational evidence from neuroscience disciplines and psychology to support the investigation of this concept after ACL injury. It is imperative for healthcare clinicians to be able to utilize such
foundational evidence to help promote a paradigm shift in rehabilitation strategies to include therapeutic interventions that have the potential to optimize psychological function by improving the neural system.
CHAPTER 3: No shortage of disagreement between biomechanical and clinical hop symmetry after ACLR

A manuscript based on the research presented in this chapter has been submitted for publication:


3.1 ABSTRACT

Background: Evaluating average performance on functional hop tasks can potentially overestimate physical function, as it masks variability present within individual trials and may lead to clinician oversight regarding the overall movement quality. The purpose was to evaluate the trial-by-trial agreement between hop-distance symmetry and knee biomechanics (knee flexion angle, knee extension moment) to reveal the full extent of agreement between these measures. Methods: Sixteen individuals with primary, unilateral anterior cruciate ligament reconstruction participated (age:22(2)y; height:1.71(0.11)m; mass:68.94(13.06)kg; gender: 8 males, 8 females; years’ post-surgery:4(3)y) in a cross-sectional study. Knee kinematics and kinetics were measured using 3D motion analysis and hop distance was collected during the triple hop for distance. Individual limb difference values for individual hop trials were calculated and values for each trial were dichotomized as pass/fail based on achieving a limb difference of less than 10%. Cohen's Kappa and confirmatory McNemar's test were performed to determine the level of agreement between measures of physical and biomechanical function between trials. Findings: No agreement between triple hop and peak knee flexion angle symmetry ($\kappa=0.033$, $p=0.387$) and peak internal knee extension moment ($\kappa=0.022$, $p=0.475$) were found. McNemar tests confirmed no agreement
between hop-distance %LD and knee flexion angle/knee extension moment %LD (p=0.000). **Interpretation:** These findings suggest that while individuals after ACLR may on average achieve symmetrical hop-distance, they may not necessarily pass subsequent functional tasks. Further, individual trial-by-trial analyses may provide insight into an individual’s true physical capability compared to simply evaluating the average, which may overestimate physical function or mask altered movement strategies. **Word Count: 250**

### 3.2 INTRODUCTION

Anterior cruciate ligament (ACL) injuries are extremely debilitating and burdensome knee joint injuries, affecting nearly 250,000 Americans annually. (Griffin, Albohm et al. 2006, Mather, Koenig et al. 2013, Hofbauer, Muller et al. 2014) Although there have been substantial advances in both surgical and rehabilitative techniques employed after ACL injury, reduced post-operative outcomes continue to persist, (Logerstedt, Di Stasi et al. 2014, Ardern 2015) where 1 in 3 individuals demonstrates reduced activity level compared to preinjury levels (Ardern, Taylor et al. 2014) and reduced long term quality of life. (Lentz, Zeppieri et al. 2012, Ardern 2015) Rehabilitation efforts after ACL reconstruction (ACLR) place a heavy emphasis on regaining physical strength and movement control during functional tasks, with the ultimate goal of obtaining limb symmetry between the involved and uninvolved limb. (Czuppon, Racette et al. 2014, Mueller, Bloomer et al. 2014) Clinical objective criteria used to gauge an individual’s functional capability after ACLR includes limb differences of less than 10% during isokinetic and isometric strength testing, as well as functional hop tasks aimed at replicating sport-related movement. (Barber-Westin and
Research has recently indicated that simply evaluating the hop distance symmetry between limbs specifically distanced hopped on functional tasks, may in fact overestimate an individual’s function. (Wellsandt, Failla et al. 2017) To address this shortcoming, researchers have moved to using biomechanical analysis during functional hopping tasks to assess asymmetrical inter-limb strategies that persist despite extensive rehabilitation programs. (Paterno, Schmitt et al. 2010, Oberlander, Bruggemann et al. 2013, Peebles, Renner et al. 2018, Welling, Benjaminse et al. 2018) Identifying these altered biomechanical characteristics is clinically meaningful, as individuals exhibiting multi-planar knee biomechanical asymmetries are three times more likely to sustain an secondary ACL injury. (Paterno, Schmitt et al. 2010) Notably, DiStasi et al (Di Stasi, Logerstedt et al. 2013) reported that 52% of athletes who failed to meet “functional hop distance limb symmetry” criteria after ACLR demonstrated larger kinematic (knee flexion angle) and kinetic (internal knee extension moment) asymmetries compared to those who passed. This finding has been replicated in an adolescent population, where obtaining functional distanced hopped limb symmetry, was not indicative of symmetrical knee landing biomechanics. (Wren, Mueske et al. 2018) Specifically, adolescents that demonstrated symmetrical hop distances, exhibited an offloading ACLR limb strategy (lower knee flexion moments and lower knee energy absorption) compared to the contralateral limb. (Wren, Mueske et al. 2018) Altogether, this body of work points to the disagreement between distance hopped symmetry and symmetrical biomechanics.
The full extent of the disagreement between these measures is unknown, as the data is most often analyzed using either average performance or “best” values. Evaluating average performance on functional hop tasks can potentially overestimate an individual’s physical function, as it may mask variability present within individual trials. For example, an individual may complete two trials poorly and one very well, which may drive up their average performance and conceal individual task results. Additionally, despite often exhibiting satisfactory average performances, lack of more critical and thoughtful evaluation of functional performance after ACLR may lead to clinician oversight regarding the overall movement quality and strategies employed during such functional tasks. In order to fully investigate the extent of disagreement between distance hopped symmetry and knee biomechanical symmetry, we purposefully sought to investigate individuals with a history of ACLR who based on average evaluation scores would pass (less than 10% between-limb difference over 3 trials) the clinical triple hop for distance (TrH) task. We then sought to evaluate the trial-by-trial agreement between distance hopped symmetry and knee biomechanics to reveal the full extent of agreement between these measures. Identifying the extent of disagreement between functional and biomechanical performance variables is clinically important, as emerging evidence suggests that these clinical hop tasks can overestimate function (Wellsandt, Failla et al. 2017) and are not indicative of biomechanical loading patterns during landing (Wren, Mueske et al. 2018). Thus, elucidating if there is any overlap or agreement between these criteria is needed in order to inform clinical decision making.
3.3 MATERIALS AND METHODS

Patients

Sixteen patients who had sustained a primary, unilateral ACL rupture and subsequently underwent ACLR were recruited from the Department of Orthopaedic Surgery at the University of Connecticut Health Center and the general student population (Table 3.1). Patients included in the study reported to the University of Connecticut, Sport Optimization and Rehabilitation Laboratory for testing where subjects were first required to perform a clinical hop task in which we concurrently evaluated 3-dimensional lower extremity biomechanics. Only patients who based on average evaluation scores would pass the clinical triple hop for distance (TrH) task were included in the subsequent analyses (6 subjects were excluded based on this criteria). Passing was defined as achieving a percent limb difference (%LD) (Equation 1) value of less or equal to than 10% for hop distance. Patients also had to meet the following criteria: 1) cleared to return to unrestricted functional activities by their orthopaedic surgeon; 2) no history of previous lower extremity surgery and 3) no contralateral lower extremity injury in the last 6 months. Patients were excluded if they: 1) if they were pregnant or planning pregnancy, 2) if they had a demand-type cardiac pacemaker and 3) if they had an allergy to adhesives or any open skin lesions. All subjects completed an informed consent form, which was approved by the University’s Institutional Review Board prior to testing.

Clinical Measures

Patients performed a single limb TrH for distance task commonly used as a component for clearance to unrestricted functional activities.(Gokeler, Welling et al.)
The TrH task has been previously utilized in larger battery of clinical tasks and was the largest predictor of patient function compared to other hop for distance tasks after ACLR. (Menzer, Slater et al. 2017) Patients were allowed unlimited practice trials. Once the patients were comfortable with performing the task, 3 successful trials were captured (Figure 3.1). The TrH hop task was performed bilaterally and the order of limb testing was randomized. Percent limb differences (%LD) were first calculated in order to compare average distance hopped between limbs on the hop task (Equation 1). (Bishop, Read et al. 2018) In order to evaluate the extent of disagreement during the clinical TrH task, %LD were also calculated across individual hop trials. Specifically, for distance hopped, the first trial for the ACLR limb was compared to the first trial for the contralateral limb. %LD were calculated for trials 2 and 3 in the same manner.

\[
\text{Equation 1: } \%LD = \left( \frac{\text{ACLR limb} - \text{Contralateral limb}}{\text{Highest value}} \right) \times 100
\]

![Figure 3.1. Clinical Single Limb Triple Hop Task](image)

Biomechanics were captured during second of the 3 hops when the participants landed and took off from the platform and then subsequently completed the final hop, where they were required to land and balance on their injured limb for at least one second.
Biomechanical Analyses

Simultaneously, sagittal plane knee kinematics and kinetics were collected during the triple hop (TrH) clinical task. A 12-camera motion capture system (Vicon, Oxford Metrics, London, England) sampling at 240Hz and synchronized with 2 force plates (Bertec Corp., Columbus, Ohio) sampling at 1200Hz was utilized. Data were collected for both ACLR and contralateral limbs. Motion capture data were collected until at least 3 successful trials were captured for each limb. A trial was considered successful when the participants hit the force platform on the second of the 3 hops and then subsequently completed the final hop, where they were required to land and balance on their injured limb for at least one second (Figure 1). Trunk and lower limb joint rotations were defined based on 3D coordinates of 37 precisely positioned retro-reflective markers (trunk; [C7 spinous process, T10 spinous process, acromioclavicular joints, sternum], right and left limbs; [anterior and posterior superior iliac spines, iliac crest, greater trochanter, distal thigh, medial and lateral femoral epicondyles, tibial tuberosity, distal shank, lateral shank, medial and lateral malleoli, calcaneus, dorsal navicular, head of first and fifth metatarsal]). A static trial (McLean, Lipfert et al. 2004) of each participant aligned with the laboratory coordinate system was recorded and a kinematic model including eight skeletal segments (bilateral foot, shank and thigh segments, pelvis and trunk) and 27 degrees of freedom was created using Visual3D software (C-Motion; Rockville, MD, USA). Marker trajectories recorded during each trial were subsequently processed within the respective subject's Visual3D model to solve for the generalized coordinates of each frame. Rotations were calculated utilizing the Cardan rotation sequence (XYZ),(Cole, Nigg et al. 1993) expressed relative to each participant’s
neutral static position. Ground reaction force data were sampled and synchronized with the kinematic data, and filtered using a fourth-order, zero-lag, low-pass Butterworth filter at a 12 Hz cut-off frequency. (McLean, Fellin et al. 2007) Filtered kinematic and ground reaction force data were submitted to a standard inverse dynamics approach within Visual3D. Knee joint moments were expressed as flexion–extension, adduction-abduction, and internal-external rotational moments with respect to the Cardan axes of the local joint coordinate system. (McLean, Fellin et al. 2007) Kinetic outputs were normalized to body height and mass, and represented as internal moments.

Biomechanical data (during the landing phase of the second hop- Figure 3.1) were time normalized across stance (100%) and initial contact and toe-off was defined as the time when the vertical ground reaction force first exceeded 10 N (McLean, Fellin et al. 2007, Borotikar, Newcomer et al. 2008) and fell below 10 N, respectively. Firstly, to compare our findings with previous literature (Di Stasi, Logerstedt et al. 2013, Wren, Mueske et al. 2018), we calculated the average kinematic and kinetic variables using the 3 trials from each subject. An overall representative movement trial was created by submitting the trial-by-trial normalized stance data to an ensemble average. Peak knee flexion angle and peak knee extension moment during landing were then obtained in order to calculate the average LD value (traditional method) (Equation 1). For the individual trials, the normalized stance data was examined to identify the peak knee flexion angle and peak knee extension moment during landing for the ACLR limb. This value was then compared to the contralateral limb for the same trial to create the individual trial LD (trial-by-trial method).
Statistical Analyses

To visually depict the average disagreement among hop distance and knee biomechanical outcome variables, a gradient map of %LD values is included in Figure 3.2. To confirm that our cohort was representative of previously published literature (Wren, Mueske et al. 2018), Pearson product moment correlations were performed to determine the overall association between average knee biomechanical variables and the average performance on the clinical TrH task. Shapiro-Wilk tests were used to determine normality and spearman’s rho correlations were performed as necessary for all non-normally distributed data. In order to determine the full extent of disagreement between clinical hop distance and biomechanical variables, individual %LD values for each individual hop trial (n=3) were calculated (Equation 1) and values for each trial were then dichotomized as either pass or fail based on the 10% cutoff value. (Barber-Westin and Noyes 2011, Grindem, Snyder-Mackler et al. 2016, Paterno, Huang et al. 2017, Renner, Franck et al. 2018) Subsequent Cohen's Kappa and confirmatory McNemar’s test were then performed on the dichotomized data (pass or fail) to determine the level of agreement between measures of clinical and biomechanical function (peak knee flexion angle, peak internal knee extension moment) within all hop trials. An additional gradient map of dichotomized data (pass/fail) for all individualized hop trials in two representative patients is presented in Figure 3.3. α-level was set a priori at $P \leq 0.05$. Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) software version 24.0 (IBM Corp., Armonk, NY, USA).
3.4 RESULTS

All participants included in the analyses (n=16) had achieved on average less than 10% limb difference during the TrH task. Patient demographics are provided in Table 3.1. In agreement with previously reported data (Wren, Mueske et al. 2018), on average our cohort displayed clinical symmetry on the TrH task that was not indicative of biomechanical symmetry (Table 3.2, Figure 3.2). Evaluation of the individual hop trials using the Cohen’s Kappa revealed the full extent of this disagreement, where no agreement between TrH hop (<10%LD) and peak knee flexion angle (KFA) symmetry (κ=0.033, p=0.387) and peak internal knee extension moment (KEM) (κ=0.022, p=0.475) (Figure 3.3) was found. Figures 3.4-3.6 also provide a visual depiction of the individual participant and trial variability and lack of agreement between achieving clinical hop distance symmetry and biomechanical symmetry strategies. Confirmatory McNemar tests reinforced the Kappa results and indicated that no agreement between clinical TrH distance and peak KFA (p=0.000) as well as peak KEM (p=0.000) were found.

Table 3.1. Patient demographics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>21.50 (2.34)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>1.71 (0.11)</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>68.94 (13.06)</td>
</tr>
<tr>
<td>Years after surgery</td>
<td>4.13 (2.78) (range 0.53-9.2)</td>
</tr>
<tr>
<td>Graft type</td>
<td>12 PT, 4 HS</td>
</tr>
<tr>
<td>Females/males</td>
<td>8 males /8 females</td>
</tr>
<tr>
<td>Tegner activity score</td>
<td>7.25 (1.39)</td>
</tr>
</tbody>
</table>

Abbreviations: HS, hamstring tendon graft; PT, bone-patellar tendon-bone graft
Table 3.2. Overall Associations Between Average Biomechanical and Clinical Hop Limb Differences

<table>
<thead>
<tr>
<th>Clinical Hop Task</th>
<th>TrH peak KFA</th>
<th>TrH peak KEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>TrH</td>
<td>r=-.48</td>
<td>r=.24</td>
</tr>
<tr>
<td></td>
<td>p=.06</td>
<td>p=.36</td>
</tr>
</tbody>
</table>

Abbreviations: ACLR, anterior cruciate ligament reconstruction; ACL-RSI, KEM, knee extension moment; KFA, knee flexion angle; TrH, triple hop for distance

Table 3.3. Lack of Agreement Between Individual Biomechanical and Clinical Hop Limb Differences

<table>
<thead>
<tr>
<th>Clinical Hop Task</th>
<th>Statistical Test</th>
<th>TrH peak KFA</th>
<th>TrH peak KEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>TrH</td>
<td>Kappa</td>
<td>κ = .033</td>
<td>κ = .022</td>
</tr>
<tr>
<td></td>
<td></td>
<td>p = .387</td>
<td>p = .475</td>
</tr>
<tr>
<td></td>
<td>McNemar</td>
<td>P &lt; 0.0001</td>
<td>P &lt; 0.0001</td>
</tr>
</tbody>
</table>

Abbreviations: ACLR, anterior cruciate ligament reconstruction; ACL-RSI, KEM, knee extension moment; KFA, knee flexion angle; TrH, triple hop for distance
<table>
<thead>
<tr>
<th>Subject 1</th>
<th>TrH peak KFA %LD</th>
<th>TrH peak KEM %LD</th>
<th>TrH Distance %LD</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.2</td>
<td>20.52</td>
<td>3.01</td>
<td></td>
</tr>
<tr>
<td>(4.80-29.65)</td>
<td>(13.95-25.60)</td>
<td>(1.03-4.64)</td>
<td></td>
</tr>
<tr>
<td>Subject 2</td>
<td>3.81</td>
<td>13.04</td>
<td>4.56</td>
</tr>
<tr>
<td>(0.55-2.63)</td>
<td>(4.52-14.87)</td>
<td>(3.20-6.62)</td>
<td></td>
</tr>
<tr>
<td>Subject 3</td>
<td>23.09</td>
<td>17.08</td>
<td>0.86</td>
</tr>
<tr>
<td>(14.97-28.71)</td>
<td>(8.10-32.41)</td>
<td>(2.57-3.41)</td>
<td></td>
</tr>
<tr>
<td>Subject 4</td>
<td>2.85</td>
<td>10.51</td>
<td>6.01</td>
</tr>
<tr>
<td>(7.35-15.66)</td>
<td>(7.82-31.03)</td>
<td>(4.99-7.85)</td>
<td></td>
</tr>
<tr>
<td>Subject 5</td>
<td>19.24</td>
<td>36.19</td>
<td>0.86</td>
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<tr>
<td>(2.41-26.10)</td>
<td>(15.23-43.33)</td>
<td>(0.93-3.99)</td>
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<td>5.46</td>
<td>5.54</td>
<td>5.67</td>
</tr>
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<td>(2.64-12.03)</td>
<td>(0.60-13.10)</td>
<td>(2.44-7.94)</td>
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<tr>
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<td>10.52</td>
<td>4.1</td>
<td>0.77</td>
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<td>(6.78-10.52)</td>
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<td>(0.47-1.39)</td>
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<tr>
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<td>1.48</td>
<td>19.1</td>
<td>5.04</td>
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<td>(0.80-32.94)</td>
<td>(0.18-9.61)</td>
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</tr>
<tr>
<td>Subject 9</td>
<td>15.84</td>
<td>2.84</td>
<td>0.98</td>
</tr>
<tr>
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<td>(0.55-11.74)</td>
<td>(0.17-1.74)</td>
<td></td>
</tr>
<tr>
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<td>6.79</td>
<td>20.98</td>
<td>6.88</td>
</tr>
<tr>
<td>(5.39-22.76)</td>
<td>(0.07-11.90)</td>
<td>(4.69-8.38)</td>
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<td>Subject 11</td>
<td>6.68</td>
<td>9.7</td>
<td>5.6</td>
</tr>
<tr>
<td>(1.87-10.74)</td>
<td>(3.01-29.15)</td>
<td>(2.85-8.10)</td>
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<td>1.2</td>
<td>7.79</td>
<td>6.31</td>
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<td>(2.13-24.37)</td>
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<td>(11.75-22.13)</td>
<td>(1.92-31.18)</td>
<td>(4.08-5.20)</td>
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<td>5.89</td>
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<td>8.74</td>
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<td>(6.14-10.75)</td>
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<td>12.22</td>
<td>3.72</td>
</tr>
<tr>
<td>(8.51-26.39)</td>
<td>(35.79-47.54)</td>
<td>(1.7-5.11)</td>
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</tbody>
</table>

Figure 3.2. Average biomechanical and clinical hop distance percent limb difference values during TrH. %LD for distance hopped, peak KFA and KEM were calculated by comparing the average peak of the ACL limb to the average peak of the contralateral limb. The range (minimum-maximum) %LD values for the three individual trials are provided for each of the tasks. Abbreviations: %LD, percent limb difference; KEM, knee extension moment; KFA, knee flexion angle; TrH, triple hop for distance.
Figure 3.3. Individual trial-by-trial biomechanical and clinical hop distance percent limb difference values during TrH

%LD for distance hopped, peak KFA and KEM were calculated by comparing the first trial for the ACL limb to the first trial for the contralateral limb. %LD were calculated for subsequent trials in the same manner.
Figure 3.4. Increased variability in clinical hop distance between individual hop trials
Individual trial %LD values for distance hopped during the TrH task. Participants are represented by individualized colored lines. The red dotted line represents the clinical LD value (of 10%) that is used to objectively quantify limb symmetry and physical function after ACLR. Agreement between trials would be indicated by more horizontal lines.

Figure 3.5. Increased variability in peak knee extension moment between individual hop trials. Individual trial %LD values for knee extension moment values during the TrH task. Participants are represented by individualized colored lines. The red dotted line represents the clinical LD value (of 10%) that is used to objectively quantify limb symmetry and physical function after ACLR. Agreement between trials would be indicated by more horizontal lines.
3.5 DISCUSSION

The purpose of this study was to describe the extent of disagreement between distance hopped symmetry and biomechanical symmetry within individual hop trials in patients who on average achieve symmetry on the clinical TrH task after ACLR. Elucidating if there is any overlap or agreement between these criteria will help clinicians better understand what these clinical functional tests are actually telling us regarding patient function and is needed in order to inform clinical decision making. This knowledge may also further help to bolster clinical adoption, as utilization of objective functional criteria is currently limited, in part, due to the extensive time and resources needed to measure these outcomes. (Barber-Westin and Noyes 2011, Barber-Westin...
Moreover, use of such objective functional criteria has been shown to significantly reduce risk of secondary ACL injury by 84% (Grindem, Snyder-Mackler et al. 2016).

The findings of the present study corroborate previous research (Wren, Mueske et al. 2018) highlighting that when evaluating average values, hop distance limb symmetry was largely unrelated to knee biomechanics employed during that task (Table 3.2), underscoring that each of these tasks (clinical versus biomechanical) are capturing different elements of neuromuscular control and physical function. Further, when evaluating trial-by-trial agreement between distance hopped symmetry and knee biomechanics, there was increased variability (Figure 3.3) and no agreement between passing clinical and biomechanical variables (Table 3.3). Given the results of this work, it is important for clinicians to consider that an individual’s symmetry and performance on single limb hops, may not reveal underlying biomechanical alterations after ACLR. Simply put, distance hopped during the clinical TrH task is not a substantial indication of how someone would biomechanically perform the same task. To this point, recent work by Birchmeier et al (Birchmeier, Lisee et al. 2019) highlights that the TrH distance may in fact be a better indicator of reactive force production, versus biomechanical measures.

Utilizing specific functional assessments is imperative not only for reducing the risk for secondary ACL injury but for promoting long term quality movement control (Grindem, Snyder-Mackler et al. 2016, Paterno, Huang et al. 2017, Ithurburn, Altenburger et al. 2018). Consequently targeting limb asymmetries, both functional (Noyes, Barber et al. 1991, Palmieri-Smith and Lepley 2015) and biomechanical (Schmitt, Paterno et al. 2014), has become a large focus after
ACL.(Renner, Franck et al. 2018) Recent research has indicated that individuals who achieved a LD within 10% for both quadriceps muscle strength and hop performance had an 84% reduction in reinjury rate upon return to sport.(Grindem, Snyder-Mackler et al. 2016) The present study evaluated a single limb clinical hop task, concurrent with biomechanical analyses, as the TrH task is a feasible objective test readily available to clinicians. Additionally, evaluation of single limb hop performance allows clinicians to identify potential movement compensations that may ultimately result in abnormal joint loading that is detrimental to long-term joint health.(Barber-Westin and Noyes 2011)

Although all patients, on average, achieved less than 10% LD on the TrH task, interestingly, more than half of patients exhibited greater than 10% LD values for the average kinematic and kinetic variables (Figure 3.2). This is consistent with recently published literature that highlights individuals who achieved symmetrical hopping distance demonstrated reduced knee loading strategies compared to the contralateral limb.(Wren, Mueske et al. 2018)

Unique to the findings of the present study, when specifically evaluating individual hop trials, there is no agreement between distance hopped and biomechanical variables. Clinicians often utilize average or peak performance on objective tasks when assessing physical function after ACLR.(Noyes, Barber et al. 1991, Barber-Westin and Noyes 2011, Wellsandt, Failla et al. 2017, Wren, Mueske et al. 2018) Additionally, studies often report on functional performances using metrics such as the limb symmetry indices or percent limb differences, which doesn’t provide a range of individual hop task values.(Thomee, Neeter et al. 2012) Unfortunately, optimal performance on specific functional tasks, such as the TrH, may not be indicative of the
majority of movement strategies employed during functional activities. Specifically, when evaluating patients’ individual hop trials, there was inherently more variability in whether or not they would have passed or failed on both distance and biomechanical movement patterns based on the pre-determined criteria of 10% LD (Figure 3). Figures 3.4-3.6 provide additional descriptive individual trial variability between clinical hop distance and biomechanical strategies utilized to complete the task. It is evident that while individuals may obtain the same hop distance between limbs, they are achieving this symmetrical distance using different knee biomechanical strategies. These findings corroborate findings by Welling et al (Welling, Benjaminse et al. 2018) that identified altered movement strategies (using a clinically feasible video assessment) despite achieving a limb symmetry index of greater than 90%. Further, our findings provide evidence that the strategies used to obtain symmetry are variable across trials. This is of clinical importance as increased variability on functional hop tasks may be more indicative of true physical function compared to simply focusing on the best or average performances when assessing functional capability. These findings also indicate that while individuals after ACLR may overall achieve satisfactory physical function on one measure, they may not necessarily complete subsequent tasks at the same level of function, nor are they performing these tasks with optimal movement/neuromuscular control.

Study limitations

The cohort of individuals included in this study was a sample of convenience from the local University population. As such, we enrolled individuals with mixed graft types, and we were not able to control for post-operative rehabilitation. Additionally, our
cohort of individuals were on average approximately 4 years removed from ACL surgery. Hence our interpretations are limited to chronic movement patterns after ACLR and may not apply to more acute timelines, though our data was in agreement with the work of others. Lastly, due to the smaller convenience sample, there was an inability to evaluate outcomes based upon gender. Future studies should consider evaluating limb differences during clinical and biomechanical tasks between males and females in a larger cohort.

3.6 CONCLUSION

The purpose of this study was to describe the extent of disagreement between distance hopped symmetry and biomechanical symmetry within individual hop trials in patients who on average achieve distance symmetry on the clinical TrH task after ACLR. There was no agreement between distance hopped and biomechanical variables during individual hop trials. These findings suggest that while individuals after ACLR may on average achieve satisfactory physical function, they may not necessarily pass subsequent functional tasks. Further, individual trial-by-trial analyses may provide better insight into an individual’s true physical capability compared to simply evaluating the overall average value, which may potentially overestimate physical function or mask altered movement strategies. It is apparent that a patient’s ability to achieve the same hop distance is not associated nor in agreement with achieving biomechanical symmetry, emphasizing the need to further consider biomechanical alterations evident after ACLR in order to provide a comprehensive representation of patient function.
CHAPTER 4. What are our patients really telling us? Psychological constructs associated with patient-reported outcomes after ACLR

A manuscript based on the research presented in this chapter has been submitted for publication:


4.1 ABSTRACT

Objective: Depressed patient-reported outcomes (PROs) are directly related to suboptimal recovery after anterior cruciate ligament reconstruction (ACLR). PROs provide a gross estimation of function, but do not fully elucidate the causes of self-perceived disability. To more fully characterize the factors driving responses on PROs, a mixed-methods approach was used, where qualitative interviews were conducted alongside PROs to uncover the themes’ behind a participant’s PRO responses. Design: Cross-sectional. Setting: Laboratory. Participants: Twenty-one individuals with unilateral-ACLR volunteered (age: 21±3y; height: 1.72±0.11m; mass: 71.10±13.36kg; years’ post-surgery: 4±3y). Interventions: PROs and qualitative perceived function were assessed. Main Outcome Measures: PROs included International Knee Documentation Committee (IKDC), Knee Injury and Osteoarthritis Outcomes Score (KOOS), ACL-Return-to-Sport after Injury (ACL-RSI) and Tampa Scale of Kinesiophobia (TSK). A hierarchical cluster analysis was used to identify sub-groups based on PROs. Qualitative interviews provided supplemental understanding of perceived function. Independent t-tests examined cluster differences on themes. Spearman’s rho correlations determined associations between PROs and themes. Results: Two
clusters (high/low function) emerged. High-function individuals scored better on all PROs (P<0.05), except for KOOS-ADL. Psychological and physical facilitators/barrier sub-themes emerged from the interviews. There was a significant difference between clusters and themes. Lower TSK, greater ACL-RSI and KOOS-QOL scores were associated with more perceived facilitators. **Conclusions:** Participants with greater internal motivation, confidence and a support network had improved PROs. Participants with avoidance tendencies, fear, lack of clear expectations and support scored worse on PROs. TSK, ACL-RSI, and KOOS-QOL scales were able to best capture constructs associated with perceived wellness, which reinforces their utility in recovery.

**Word Count:** 249

**Key Words:** self-reported function, ACL, clinical thresholds, psychology

**Abbreviations:** Anterior cruciate ligament, ACL; ACL reconstruction, ACLR; ACL Return to Sport after Injury, ACL-RSI; activities of daily living, ADL; International Knee Documentation Committee form, IKDC; Knee Injury and Osteoarthritis Outcome Score, KOOS; patient reported outcome, PRO; Tampa Scale of Kinesiophobia, TSK; quality of life, QOL

### 4.2 INTRODUCTION

Anterior cruciate ligament (ACL) injuries are debilitating injuries that result in a series of negative consequences that persist well after an individual ceases formal rehabilitation.(Logerstedt, Di Stasi et al. 2014, Ardern 2015) For instance, it is well known that those with a history of ACLR are at high risk for early joint degeneration(Cinque, Dornan et al. 2017, Bodkin, Werner et al. 2019) and a lifetime of reduced physical activity. Psychological wellness is also disrupted,(Logerstedt, Di Stasi et al. 2014, Ardern and Kvist 2015, Burland, Toonstra et al. 2018) as those with a

Deficits in physical wellness have been well studied, (Palmieri-Smith, Thomas et al. 2008, Ardern, Webster et al. 2011, Lepley 2015, Lai, Ardern et al. 2018, Lisee, Lepley et al. 2019) yet psychological recovery is less understood. Comprehensive medicine requires an understanding of both the physical and psychological factors that influence recovery. (Tjong, Murnaghan et al. 2014) Work that can continue to fill the gap by elucidating the psychological factors that influence recovery is desperately needed.

In response to this growing understanding of psychological function as an important component for general wellness after ACLR, research has emphasized the importance of capturing perceived function in the form of patient reported outcomes (PROs). (Logerstedt, Di Stasi et al. 2014, Lepley 2015, Burland, Toonstra et al. 2018, Lepley, Pietrosimone et al. 2018, Werner, Burland et al. 2018) PROs that measure function, pain, symptoms, and/or quality of life have commonly been reported in the literature (e.g. International Knee Documentation Committee [IKDC] form; Knee Injury and Osteoarthritis Outcome Score [KOOS]). (Roos, Roos et al. 1998, Swinkels-Meeuwisse, Swinkels et al. 2003, Webster, Feller et al. 2008, Collins, Misra et al. 2011)

Additionally, scales that look at fear of movement, pain, or re-injury, or readiness to return to sport, continue to gain attention (Tampa Scale of Kinesiophobia [TSK]; ACL Return to Sport after Injury [ACL-RSI] scale) as activity rates and reinjury risks are of large clinical concern. (Grindem, Snyder-Mackler et al. 2016, Paterno, Huang et al. 2017, Zarzycki, Failla et al. 2018)
Published data exists on clinical cutoffs or patient acceptable symptom state thresholds (Muller, Yabroudi et al. 2016) for common PROs (Table 4.1) that can provide information on clinically meaningful scores corresponding to overall health state. (Muller, Yabroudi et al. 2016) While PROs provide us with a quantifiable numerical value representing patient perceived function, they do not account for the underlying drivers of those responses. Thus, it is difficult to fully and appropriately interpret PRO scores and meaningful thresholds within clinical practice, reducing the clinical utility of these scales. Identifying what factors drive lower responses on PROs can help clinicians to understand the barriers to recovery in patients that are at risk for poor psychological health after ACLR. Thus, using a mixed methods approach, the purpose of this study was to uncover the themes’ behind a participant’s PRO responses using qualitative interviews. The strength of this design is that mixed methodology enables us to capture important aspects of therapy that cannot be reduced into a numerical form and are best conveyed through patient interaction. This approach will allow us to fill a vital gap in the literature by more fully understanding the barriers that disrupt recovery after ACLR.

4.3 METHODS

A cross-sectional, mixed methods study design was used to comprehensively assess perceived knee function in patients who had undergone ACLR. Participants were included if they met the following criteria: 1) had undergone primary, unilateral ACLR, 2) were cleared to return to unrestricted functional activities by their orthopaedic surgeon, 3) had no history of previous lower extremity surgery, 4) had no contralateral lower extremity injury in the last 6 months, and 5) understood and spoke English. During a single session, participants completed a battery of PROs and then participated in a
one-on-one qualitative interview to explore factors related to perceived knee function after ACLR. We continuously enrolled participants who matched our eligibility requirements based both on an a priori power analysis (based on the ACL-RSI) (Muller, Kruger-Franke et al. 2015) that determined the number of participants (n=17) and additionally until data saturation was achieved. (Creswell 2007) A total of 21 individuals were recruited and participated in the study. Additional demographic variables are outlined in Table 4.2. Participants were provided with both verbal and written information regarding completion of the patient reported outcome scales as well as details regarding the interview process and involvement was voluntary. The study was approved by the University Institutional Review Board, informed consent was obtained before data collection, and participants were assured of confidentiality.
### Table 4.1. Clinical Cutoff Scores and PASS Thresholds for Patient Reported Outcome Measures

<table>
<thead>
<tr>
<th>Patient Reported Outcome</th>
<th>Score Range</th>
<th>Clinical PASS Threshold</th>
<th>Domain Description</th>
<th>Score Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKDC</td>
<td>0-100</td>
<td>≥ 75.9</td>
<td>Knee specific measures of function, symptoms and sport specific activity</td>
<td>Higher score is better</td>
</tr>
<tr>
<td>KOOS Pain</td>
<td>0-100</td>
<td>≥ 88.9</td>
<td>Pain</td>
<td>Higher score is better</td>
</tr>
<tr>
<td>KOOS Symptoms</td>
<td>0-100</td>
<td>≥ 57.1</td>
<td>Knee symptoms</td>
<td>Higher score is better</td>
</tr>
<tr>
<td>KOOS Activities of Daily Living</td>
<td>0-100</td>
<td>=100</td>
<td>Knee function during ADLs</td>
<td>Higher score is better</td>
</tr>
<tr>
<td>KOOS Quality of Life</td>
<td>0-100</td>
<td>≥ 62.5</td>
<td>Knee factors affecting quality of life</td>
<td>Higher score is better</td>
</tr>
<tr>
<td>KOOS Sports</td>
<td>0-100</td>
<td>≥ 75.0</td>
<td>Knee function during sports specific tasks</td>
<td>Higher score is better</td>
</tr>
<tr>
<td>TSK (George, Lentz et al. 2012)</td>
<td>17-68</td>
<td>≤ 37</td>
<td>Fear of reinjury, kinesiophobia</td>
<td>Lower score is better</td>
</tr>
<tr>
<td>ACL-RSI (Webster, Feller et al. 2008, Langford, Webster et al. 2009)</td>
<td>0-100</td>
<td>≥ 56</td>
<td>Readiness to return to functional activities; patient confidence and risk appraisal</td>
<td>Higher score is better</td>
</tr>
</tbody>
</table>

Abbreviations: ACL-RSI; Anterior Cruciate Ligament Return to Sport after Injury; IKDC, International Knee Documentation Committee; KOOS, Knee Osteoarthritis Outcome Score; PASS, Patient Acceptable Symptom Score; TSK, Tampa Scale of Kinesiophobia

### Table 4.2. Participant Demographics

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
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<tbody>
<tr>
<td>Age</td>
<td>20.90 ± 2.86</td>
</tr>
<tr>
<td>Gender</td>
<td>11 females, 10 males</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>172.0 ± 11.03</td>
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<tr>
<td>Mass (kg)</td>
<td>71.52 ± 13.59</td>
</tr>
<tr>
<td>Years since surgery</td>
<td>3.66 ± 3.03</td>
</tr>
<tr>
<td>Graft Type</td>
<td>16 PT, 5 HS</td>
</tr>
</tbody>
</table>

Abbreviations: HS, hamstring; PT, patellar tendon
Outcome Measures

Participants completed a battery of PROs which included the IKDC, KOOS subscales, ACL-RSI, and TSK (Table 4.1). These scales are commonly used to measure knee function, pain, symptoms, quality of life, readiness to return to functional activities, and fear of reinjury, respectively.

Following the completion of the PROs, we conducted exploratory qualitative semi-structured interviews to provide a deeper supplemental understanding of barriers and facilitators influencing recovery after ACLR. Data were collected through the use of a pilot tested, semi-structured interview guide (Appendix A) which was used to maintain consistency of questions. All interviews were conducted by the primary author (XX), lasted approximately 10-15 minutes and were digitally recorded and transcribed verbatim.

Qualitative data were analyzed using a general inductive approach. (Thomas 2006) Compared to other methods of qualitative analyses such as phenomenology (which seeks to uncover the meaning that lives within a shared experience) the general inductive approach derives concepts or themes through interpretations of raw participant data to support research objectives. (Thomas 2006) Each of the transcribed interviews (n=21) were initially read by three separate researchers to acquire an understanding of the participants' experiences, values and their responses regarding their experience following ACLR. Researchers performed multiple readings of the qualitative data to appropriately identify themes and categories that emerged from the data. Transcripts were coded, allowing a coding frame to be developed. If new codes emerged, the coding frame was altered to include the new code and transcripts were re-
analyzed to incorporate the new ‘term’. Once all inductive codes were identified within the transcripts, common findings were categorized together and finally conceptualized into broad themes representing the participants’ perceptions and experiences after ACLR.

Several methods were utilized to establish credibility and trustworthiness of the data. Prior to the start of the interview, a highly experienced qualitative researcher (XX) reviewed the interview guide for content, clarity and topic flow. Additionally, piloting of the interview guide was conducted. Revisions to the interview guide were made as necessary based on peer feedback. A researcher well-versed in qualitative analyses (XX) reviewed and challenged developing categories and themes identified during the multiple-analyst triangulation to ensure credibility and to minimize bias in the interpretation of results. A peer reviewer then classified 295/389 codes (75% of the data) into a particular sub-theme with 96% accuracy. Triangulation between multiple researchers (XX, XX) and peer review by an experienced researcher (XX) ensured that the data analysis process appropriately represents the emergent themes from the interviews. Additionally generated themes were circulated by e-mail to each participant for member-checking. (Thomas 2006, Creswell 2007) The purpose of member-checking was to provide each participant the opportunity to read the exhaustive description of themes to assure that it accurately represented their experience and perceptions regarding their perceived function after ACLR. We received verification from all patients that the generated themes accurately depicted their experience; no modifications were suggested. The distribution of themes reported by each participant was calculated by
taking the number of statements or codes stated for a specific theme and dividing by the total number of statements/codes stated by the participant for each overarching theme.

**Statistical Analyses**

Participant demographics and descriptive information on PROs can be found in Tables 4.1-4.3. A four-step analysis process was used to explore what factors influenced participant responses on PROs and how PROs were related to psychological function. We performed a hierarchical cluster analysis using Ward’s cluster method based off of the Squared Euclidean distance to categorize participants based on their responses on the PROs. (Cruz-Almeida, King et al. 2013) To identify which PRO measure was driving the difference between clusters, independent t-tests were performed comparing PRO scores between high and low function clusters. To determine if there were differences in qualitative theme distributions between clusters independent t-tests were performed. Lastly, in order to provide a clinical link between PROs and factors influencing patient responses, spearman’s rho correlations were performed to determine the association between PROs and the qualitative subtheme distributions.

### 4.4 RESULTS

The hierarchical cluster analysis revealed 2 clusters that were defined as high function & low function. Eleven participants were classified as high function, and 10 were designated as low function (Table 4.3). Independent t-tests following the cluster analysis revealed that individuals in the high function cluster (n=11), scored better on all measures of PROs (P <0.05), except on the KOOS ADL, where there was no significant
differences between groups (P=0.061). The KOOS QOL subscale demonstrated large group differences and predicted 85% of the variance between clusters.

Qualitative data analysis revealed 2 overarching themes (psychological and physical factors), with 4 independent subthemes (psychological facilitators, psychological barriers, physical facilitators, physical barriers). The description of each subtheme with example participant statements are provided for context in Table 4.4. Additional supplementary participant quotes specific to each subtheme are also referenced in Table 4.4 and can be found in Appendix B. The distributions of statements by subtheme and cluster differences were calculated and are presented in Table 4.5. There was a significant difference between clusters for the distribution of reported statements related to psychological subthemes (Table 4.5). Spearman’s rho correlations revealed significant associations between the TSK, ACL-RSI, KOOS-QOL scales and qualitative themes (Table 4.6).
### Table 4.3. Patient reported function cluster analysis

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<tr>
<th>Study ID</th>
<th>IKDC</th>
<th>KOOS Pn</th>
<th>KOOS Sx</th>
<th>KOOS ADL</th>
<th>KOOS Sport</th>
<th>KOOS QOL</th>
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<th>ACL-RSI</th>
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<td>90.00</td>
<td>81.25</td>
<td>35.00</td>
<td>83.33</td>
</tr>
<tr>
<td>12</td>
<td>58.62</td>
<td>94.00</td>
<td>86.00</td>
<td>100.00</td>
<td>65.00</td>
<td>56.00</td>
<td>35.00</td>
<td>50.00</td>
</tr>
<tr>
<td>15</td>
<td>71.26</td>
<td>89.00</td>
<td>75.00</td>
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<td>50.00</td>
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<td>92.00</td>
<td>79.00</td>
<td>97.00</td>
<td>75.00</td>
<td>56.00</td>
<td>26.00</td>
<td>66.66</td>
</tr>
<tr>
<td>Average</td>
<td>72.73</td>
<td>86.64</td>
<td>79.28</td>
<td>96.98</td>
<td>74.09</td>
<td>64.18</td>
<td>35.73</td>
<td>59.23</td>
</tr>
</tbody>
</table>

**P-value**

- p<0.0001
- p<0.005
- p=0.033
- p=0.061
- p<0.0001
- p<0.0001
- p<0.0001
- p<0.0001
- p<0.0001

Abbreviations for Table 4: ACL-RSI; Anterior Cruciate Ligament Return to Sport after Injury; ADL, Activities of Daily Living; IKDC, International Knee Documentation Committee; KOOS, Knee Osteoarthritis Outcome Score; Pn, Pain; QOL, Quality of Life; Sx, Symptoms; TSK, Tampa Scale of Kinesiophobia
Table 4.4. Themes and sub-theme descriptions.

<table>
<thead>
<tr>
<th>Theme</th>
<th>Sub-Theme</th>
<th>Description</th>
<th>Example Participant Statements</th>
</tr>
</thead>
</table>
| Psychological Factors | Psychological Facilitators | • Individual motivation towards recovery  
• Feelings of influence over recovery progress (internal locus of control)  
• Desire to return to previous levels of activity,  
• Confidence in affected limb | Participant 13: “Push yourself but not too much, know your body…I have faith that my leg can do it.” [Supplementary quotes 1-2]                                                                                                                                                                                                                                                 |
|                     | Psychological Barriers   | • Avoidance behaviors, mental blocks to activity participation  
• Fear of reinjury  
• Feelings of incapacity in injury event/process  
• Negative emotions regarding event and rehabilitation progress | Participant 12: “I don’t do a lot of the same activities as a lot of other people…I feel like I’m actually still a little less confident in what I can do versus what I actually can do because I’m still worried that deep down I’m going to do something to mess everything up again.”  
Participant 17: “I think the most difficult part, because it was such a long recovery, was the slowness of it. It was so frustrating at times that I couldn’t do the simplest things.” [Supplementary quotes 3-5] |
| Physical Factors    | Physical Facilitators    | • Encouragement from friends, teammates and coaches  
• Physical support to involved knee such as bracing and strength training  
• Clear expectations of the rehabilitation process | Participant 10: “My parents and even my friends were unbelievable [helpful]” [Supplementary quotes 6-10]                                                                                                                                                                                                                                                             |
|                     | Physical Barriers        | • Limitations in coverage of treatment  
• Physical factors (pain, ROM, etc)  
• Inattention of providers to individual’s status | Participant 18: “I’m having a hard time sometimes when I cut, like I feel it tighten sometimes…and sometimes when I do squats I lean more to my right side.”  
Participant 20: “Sport specific skills are definitely not the same.” [Supplementary quotes 11-14]                                                                                                                                                                                                                                      |
Table 4.5. Percentage of Theme Related Statements Reported by Each Participant and Cluster Differences

<table>
<thead>
<tr>
<th>Study ID</th>
<th>Psychological Facilitators (%)</th>
<th>Psychological Barriers (%)</th>
<th>Physical Facilitators (%)</th>
<th>Physical Barriers (%)</th>
<th>Cluster (High/Low Function)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>61</td>
<td>39</td>
<td>50</td>
<td>50</td>
<td>High</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>55</td>
<td>85</td>
<td>15</td>
<td>High</td>
</tr>
<tr>
<td>5</td>
<td>45</td>
<td>55</td>
<td>73</td>
<td>27</td>
<td>High</td>
</tr>
<tr>
<td>7</td>
<td>64</td>
<td>36</td>
<td>85</td>
<td>15</td>
<td>High</td>
</tr>
<tr>
<td>9</td>
<td>90</td>
<td>10</td>
<td>64</td>
<td>36</td>
<td>High</td>
</tr>
<tr>
<td>10</td>
<td>53</td>
<td>47</td>
<td>82</td>
<td>18</td>
<td>High</td>
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<tr>
<td>13</td>
<td>53</td>
<td>47</td>
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<tr>
<td>14</td>
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<td>57</td>
<td>High</td>
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<tr>
<td>16</td>
<td>45</td>
<td>55</td>
<td>61</td>
<td>39</td>
<td>High</td>
</tr>
<tr>
<td>19</td>
<td>22</td>
<td>78</td>
<td>38</td>
<td>62</td>
<td>High</td>
</tr>
<tr>
<td>21</td>
<td>80</td>
<td>20</td>
<td>100</td>
<td>0</td>
<td>High</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>56 ± 18</td>
<td>44 ± 18</td>
<td>64 ± 23</td>
<td>36 ± 23</td>
<td>*P=0.001</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>80</td>
<td>31</td>
<td>69</td>
<td>Low</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>80</td>
<td>43</td>
<td>57</td>
<td>Low</td>
</tr>
<tr>
<td>6</td>
<td>43</td>
<td>57</td>
<td>32</td>
<td>68</td>
<td>Low</td>
</tr>
<tr>
<td>8</td>
<td>22</td>
<td>78</td>
<td>47</td>
<td>53</td>
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<tr>
<td>11</td>
<td>25</td>
<td>75</td>
<td>19</td>
<td>81</td>
<td>Low</td>
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<tr>
<td>12</td>
<td>50</td>
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<td>50</td>
<td>Low</td>
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<tr>
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<td>76</td>
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<tr>
<td>18</td>
<td>50</td>
<td>50</td>
<td>75</td>
<td>25</td>
<td>Low</td>
</tr>
<tr>
<td>20</td>
<td>24</td>
<td>76</td>
<td>69</td>
<td>31</td>
<td>Low</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>30 ± 12</td>
<td>70 ± 12</td>
<td>46 ± 18</td>
<td>54 ± 18</td>
<td>*P=0.001</td>
</tr>
</tbody>
</table>
Table 4.6. Correlations between patient reported outcome scores and qualitative themes

<table>
<thead>
<tr>
<th>Patient Reported Outcome</th>
<th>Psychological Facilitators</th>
<th>Psychological Barriers</th>
<th>Physical Facilitators</th>
<th>Physical Barriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKDC</td>
<td>ρ=.331, p=.143</td>
<td>ρ=.331, p=.143</td>
<td>ρ=.397, p=.075</td>
<td>ρ=.397, p=.075</td>
</tr>
<tr>
<td>KOOS pain</td>
<td>ρ=.225, p=.327</td>
<td>ρ=.225, p=.327</td>
<td>ρ=.254, p=.266</td>
<td>ρ=.254, p=.266</td>
</tr>
<tr>
<td>KOOS ADL</td>
<td>ρ=.095, p=.683</td>
<td>ρ=.095, p=.683</td>
<td>ρ=.055, p=.812</td>
<td>ρ=.055, p=.812</td>
</tr>
<tr>
<td>KOOS QOL</td>
<td>ρ=.428, p=.05*</td>
<td>ρ=.428, p=.05*</td>
<td>ρ=.327, p=.148</td>
<td>ρ=.327, p=.148</td>
</tr>
<tr>
<td>TSK</td>
<td>ρ=.689, p=.001*</td>
<td>ρ=.689, p=.001*</td>
<td>ρ=.513, p=.017*</td>
<td>ρ=.513, p=.017*</td>
</tr>
<tr>
<td>ACL-RSI</td>
<td>ρ=.651, p=.001*</td>
<td>ρ=.651, p=.001*</td>
<td>ρ=.548, p=.01*</td>
<td>ρ=.548, p=.01*</td>
</tr>
</tbody>
</table>

Abbreviations: ACL-RSI; Anterior Cruciate Ligament Return to Sport after Injury; ADL, Activities of Daily Living; IKDC, International Knee Documentation Committee; KOOS, Knee Osteoarthritis Outcome Score; Pn; Pain; QOL, Quality of Life; Sx, Symptoms; TSK, Tampa Scale of Kinesiophobia

4.5 DISCUSSION

The purpose of this study was to more fully characterize the psychological factors driving responses on PROs using a mixed-methods approach. As many of these PROs can provide context regarding long-term physical and psychological wellness, it is important for clinicians to be able to appropriately utilize these tools when directing care after ACLR. Understanding how other underlying perceptions that are often not captured through traditional PROs influence overall outcomes and general wellness after ACLR is clinically valuable information. This information can be used to identify individuals that do not perceive themselves “well” and who may have greater disability. Further, exploration of factors that drive an individual’s high or low response on PROs may help to identify constructs during the recovery phase that may influence long term health and quality of life, providing a viable opportunity for the application of clinical interventions.
Not surprisingly, the findings of this study emphasize that there are broad variations in patient perceived function that can surface in the years after ACLR. The results of the cluster analysis (Table 4.3) provides clear evidence that failure to address both physical and psychological barriers throughout recovery may promote greater disability and lower quality of life in some patients after ACLR (i.e. low function cluster). Our cluster analysis was further supported by between cluster comparisons which revealed that there were significant differences between high and low function clusters on all but one PRO measure (Table 4.3), the KOOS ADL (P = 0.06), demonstrating that this particular scale may have limited utility after ACLR. Notably, the KOOS-QOL subscale was the factor that largely distinguished the difference between high and low function clusters.

There were significant differences in qualitative themes (psychological and physical facilitators/barriers) between high and low function clusters (Table 4.5). Participants in the high function cluster had a higher presence of psychological and physical facilitators, where they reported greater internal motivation/internal locus of control, confidence, a stable support network and clear expectations of the recovery process. Alternatively, more psychological and physical barriers were found in the low cluster group with individuals reporting greater avoidance tendencies, fear of reinjury, physical symptoms, and limitations to post-operative rehabilitation. These findings are of clinical importance and agree with previous literature (Tracey 2003, te Wierike, van der Sluis et al. 2013, Christino, Fantry et al. 2015, Burland, Toonstra et al. 2018, Webster, Nagelli et al. 2018) as they provide direct emphasis that individuals who demonstrate greater psychological facilitators demonstrate improved patient reported function. This is
Further corroborated by the finding that individuals who report greater psychological distress perform worse on PROs.

In order to provide clinicians with a feasible way to identify potential barriers during recovery in patients who may be at risk for poor psychological health after ACLR, we established a link between PROs and our qualitative findings. In our study, individuals who scored better on the TSK, ACL-RSI and KOOS-QOL reported more psychological facilitators, which included greater internal motivation, more confidence and desire to return to physical activities. Those with better scores on the TSK and ACL-RSI also reported more physical facilitators including greater social support, support from rehabilitation specialist, and better understanding of what to expect after surgery and throughout recovery. These findings indicate that the TSK and ACL-RSI scales have the ability to capture constructs related to both psychological and physical function.

Previous data has supported the understanding that greater fear of reinjury and less readiness to resume functional activities are associated with suboptimal outcomes after ACLR, including higher risk of reinjury and reduction or cessation of sports participation. (Webster, Nagelli et al. 2018, McPherson, Feller et al. 2019) Our study supports similar findings where individuals who scored worse on the TSK, ACL-RSI and KOOS-QOL reported greater percentages of fear of reinjury and avoidance type behaviors during their interview sessions. Specifically, these individuals emphasized that they felt they would have benefitted from additional activity-specific rehabilitation therapy, dedicated to increasing confidence and self-efficacy during the reintegration of functional movement patterns (Table 4.4). Individuals with greater fear (TSK) and less
readiness to resume functional activities (ACL-RSI) also reported experiencing more physical barriers after ACLR such as persistent knee symptoms, inability to continue rehabilitation due to insurance limitations, and less support from individual healthcare providers. Together, these findings indicate that using these clinically derived scales can identify underlying barriers to successful outcomes after ACLR. Further, they may be helpful to clinicians when making decisions regarding resumption and continuation of physical activity, as well as an indication of overall quality of life. As many of these barriers and facilitators influencing recovery are modifiable if recognized appropriately, it is important to consider the potential intervention strategies that can be utilized to mitigate these factors. Utilization of feasible interventions that bolster psychological function including guided imagery (Maddison, Prapavessis et al. 2012, Rodriguez, Marroquin et al. 2018), goal setting (Sonesson, Kvist et al. 2017) and relaxation techniques (Coronado, Bird et al. 2018) may prove beneficial throughout recovery after ACLR and may help promote better long-term quality of life.

PRO scales that are developed to assess constructs related to psychological factors may provide clinicians with a more accurate understanding on an individual’s perceived function, as none of the PRO scales strictly evaluating physical joint function were associated with any qualitative themes. The TSK and ACL-RSI were associated with both psychological and physical facilitators/barriers (Table 4.6) whereas the KOOS-QOL was only associated with psychological factors. These findings support that using the TSK, ACL-RSI and KOOS-QOL may be helpful in identifying those individuals who may benefit from additional support and/or psychological counseling. The TSK and ACL-RSI also can provide information on who may be at risk for greater physical
disability due to psychological dysfunction in the years after ACLR. When clinical time is limited, utilizing scales and established thresholds to identify those patients requiring additional individual attention may serve as a valuable tool.

**Limitations**

The cohort of individuals included in this study was a sample of convenience from the local University population. As such, we enrolled individuals with mixed graft types, and we were not able to control for post-operative rehabilitation. Additionally, our cohort of individuals were on average approximately 3 years removed from ACL surgery. Hence, their ability to recall specific information regarding their recovery may have been different compared with acute recall. It is interesting to note that many of our participants, despite being several years removed from ACLR, still did not pass clinical thresholds on several PRO measures (Table 4.3). This may indicate that individuals who experience more obstacles or barriers during recovery may have a more difficult time leading an active, healthy lifestyle after ACLR. Lastly, due to the smaller convenience sample, there was an inability to evaluate outcomes based upon gender, time from injury, current age, or age at time of surgery. Future studies should consider evaluating patient reported outcomes and perceived function during earlier stages of rehabilitation after ACLR.

**4.6 CONCLUSION**

The findings of this study support the need to consider psychological wellness after ACLR. PROs aimed at evaluating psychological deficits, specifically the TSK, ACL-RSI and KOOS-QOL have the ability to capture both psychological and physical constructs influencing perceived wellness. Utilization of these outcome tools can be
helpful in identifying individuals who would benefit from additional support and/or psychological counseling. Most importantly these data highlight that recognizing and addressing common facilitators (i.e. greater internal locus of control, confidence, social support, clear expectations) and barriers (i.e. avoidance behaviors/fear, insurance limitations) during recovery can help improve an individual’s ability to maintain overall physical health and quality of life.
CHAPTER 5. Learned Helplessness after Anterior Cruciate Ligament Reconstruction: An Altered Neurocognitive State?

A manuscript based on the research presented in this chapter has been accepted for publication:


5.1 ABSTRACT

Traumatic knee injuries, such as anterior cruciate ligament (ACL) sprains, have detrimental effects on long-term health as they initiate a cycle of chronic pain, physical inactivity, and disability. Alterations in strength and neural activity are factors that contribute to rehabilitation failure after ACL reconstruction (ACLR); however, psychological deficits also hinder rehabilitative success. Neural impairments observed following injury and ACLR may be associated with psychological dysfunction, a phenomenon defined as learned helplessness (LH). The proposed framework establishes the link between depressed neural activity and psychological dysfunction after ACL injury using foundational evidence from neuroscience and psychology to support the integration of LH into recovery.

Key Points:

- Learned helplessness (LH), a well demonstrated phenomenon in both animal and chronic disease literature, is based on a theoretical model of uncontrollability (experiences of injuries that foster a perceived lack of control) that occurs following neurological impairments. These concepts suggest an interaction
between altered neural activity and psychological wellness that can negatively influence recovery following injury.

- Psychological factors (fear avoidance, self-efficacy and stress / lack of social support) arising after anterior cruciate ligament reconstruction (ACLR) have been identified as potential contributors toward poor post-operative outcomes.
- Neural alterations resulting in neuromuscular dysfunction are also common after ACL injury and play a key role in regaining optimal physical function.
- Using foundational evidence from neuroscience and psychology disciplines, here we propose a direct link between depressed neural activity and psychological dysfunction after ACLR, applying the LH model to these patients.

5.2 INTRODUCTION

Anterior cruciate ligament (ACL) injuries are among the most debilitating injuries in athletic populations, at an annual lifetime cost of nearly $8 billion. (Griffin, Albohm et al. 2006, Mather, Koenig et al. 2013) Despite continued advances in surgical and rehabilitative techniques, post-operative outcomes are suboptimal, (Logerstedt, Di Stasi et al. 2014, Ardern 2015) with almost 40% of individuals demonstrating decreased activity levels (Ardern, Taylor et al. 2014) and reduced quality of life post-operatively. (Lentz, Zeppieri et al. 2012) Extensive rehabilitative strategies exist to restore quadriceps strength after ACL reconstruction (ACLR); however, a significant number of individuals return to functional activity with long-term quadriceps strength deficits. (Lepley 2015) Additionally, individuals who undergo ACLR have an increased risk for long-term complications compared with healthy individuals. (Yabroudi, Bjornsson
et al. 2016) For instance, re-injury to the affected limb occurs in at least 5 to 15% of ACLR individuals (Salmon, Russell et al. 2005, Yabroudi, Bjornsson et al. 2016) and younger athletes, especially those under the age of 25, have a secondary ACL injury rate as high as 23%. (Wiggins, Grandhi et al. 2016) Notably, the development of posttraumatic osteoarthritis (PTOA) after ACLR occurs in approximately 11%, 20% and 52% of individuals within 5, 10 and 20 years, respectively. (Cinque, Dornan et al. 2017) Due to suboptimal postoperative outcomes, lower than expected return to sport rates, (Bauer, Feeley et al. 2014, Ardern, Taylor et al. 2015, Dingenen and Gokeler 2017) and the risk for early onset PTOA, (Keays, Newcombe et al. 2010, Luc, Gribble et al. 2014, Harkey, Luc et al. 2015, Cinque, Dornan et al. 2017) current ACLR rehabilitation practices need to be re-evaluated to identify areas, or components, where modifications can be implemented to provide better comprehensive care.

Contemporary ACLR rehabilitation strategies largely aim to restore quadriceps strength, (Hopkins and Ingersoll 2000) neuromuscular control, and appropriate limb symmetry during functional performance tasks. (Delay, Smolinski et al. 2001, Heijne, Axelsson et al. 2008, Van Grinsven, Van Cingel et al. 2010, Failla, Arundale et al. 2015, Dingenen and Gokeler 2017) Rising awareness in the literature has also identified psychological function as a critical component to rehabilitative success; (Logerstedt, Di Stasi et al. 2014, Ardern and Kvist 2015) however, psychological function is often overlooked. Previous research supports the notion that an individual’s decision to return to sport after injury may be influenced by modifiable psychological factors, such as fear of reinjury (avoiding certain behaviors or movements due to perceived fear (Waddell, Newton et al. 1993, Ross 2010)) and kinesiophobia (debilitating fear of physical
movement or activity resulting from a feeling of vulnerability due to painful injury or reinjury).(Kori, Miller et al. 1990, Langford, Webster et al. 2009, Tjong, Murnaghan et al. 2014, Ardern 2015, Burland, Toonstra et al. 2018) These factors are well established cognitive barriers that inhibit successful rehabilitation outcomes and reintegration into sports.(Tjong, Murnaghan et al. 2014, Burland, Toonstra et al. 2018) To date, these documented psychological conditions have been restricted to only the cognitive well-being of the patient. A broader examination of psychological states, however, considers the interconnection between psychological distress and altered patterns of neural activity, a psychological behavior known as learned helplessness (LH).(Salomons, Moayedi et al. 2012)

The LH paradigm is based on a theoretical model of uncontrollability (experiences or injuries that foster a perceived lack of control) that occurs following neurological impairments, where individuals believe that their ability to achieve a specific task is not within their control.(Maier 1976, Salomons, Moayedi et al. 2012) In these cases, neural impairments, such as motor deficits of the involved limb, interact with psychological function, negatively influencing the ability of the individual to perform a desired task, creating a psychological response in that individual to either avoid that task altogether, or a distressed feeling that they can no longer complete that task. This maladaptive motor and behavioral alteration in response to neural compromise and uncontrollability is a hallmark characteristic of LH.(Salomons, Moayedi et al. 2012, Maier and Seligman 2016) Though LH has been cited as a key culprit in the psychological distress in other neurologically mediated conditions (Taub, Crago et al. 1994, Taub, Uswatte et al. 2003, Nakling, Aarsland et al. 2017), LH may also play an
important role in recovery after ACLR, given the inherent link between neurological
deficits and psychological distress after ACLR. (Klein, Fencil-Morse et al. 1976, Samwel,
Evers et al. 2006)

The current standard of care after ACLR largely ignores psychological
dysfunction as a critical component to target during rehabilitation, and as stated above,
LH may have an impact on successful outcomes following ACLR. Given the mounting
evidence supporting the presence of and impact of psychological distress after ACLR,
the purpose of this theoretical framework is four-fold: 1) to provide an overview of the
historical context of LH after traumatic events; 2) to describe psychological and neural
consequences after ACLR; 3) to conceptually describe the presence of LH after ACLR;
and 4) to propose rehabilitation therapies that may help to mitigate LH.

5.3 HISTORICAL CONTEXT OF THE LEARNED HELPLESSNESS

PHENOMENON

Though the application of LH to ACLR rehabilitation is a novel paradigm, the
presence of LH after injury is not a new concept. LH was originally described in 1976 in
an animal model as a behavior occurring in response to uncontrollable stress or an
inescapable stimuli. (Maier 1976) Exposure to such conditions was shown to increase
stress responses and to cause deficits in learning and motivation, as evidenced by
submissive and helpless behavior in rodents and dogs. (Taub, Uswatte et al. 2006,
Salomons, Moayedi et al. 2012, Kim, Perova et al. 2016) Taub et al. (Taub, Uswatte et al.
2006) expanded the early LH theory and developed a similar concept of learned limb
nonuse following deafferentation (sensation surgically removed) of monkeys. Following
deafferentation, attempted use of the deafferented limb caused failure of task
completion and aversive events. Thus, due to lack of sensory input, the monkeys would learn and adapt by using avoidance strategies, even though they possessed the sufficient motor innervation to move their limb. Similarly, Taub et al. (Taub, Uswatte et al. 2006) described that in humans, individuals who are exposed to stressful, uncontrollable situations, or chronic disease, demonstrate a learned inability to successfully complete a task or feel that the outcome of the situation is out of their control. LH has been well demonstrated in both animal and chronic disease literature (Taub, Uswatte et al. 2006, Salomons, Moayedi et al. 2012, Kim, Perova et al. 2016) in response to traumatic injury, neural alterations and uncontrollable situations, and can result in motor deficits, impaired motor patterns, reduced motivation and psychological deficits. (Klein, Fencil-Morse et al. 1976, Samwel, Evers et al. 2006, Salomons, Moayedi et al. 2012) The central tenet of LH is that a direct interaction exists between psychological and neural factors, which can negatively influence recovery following injury. In the subsequent sections, this paper will describe the psychological and neural impairments that occur following ACLR, and how the interaction of these deficiencies supports the theory of LH in these patients.

5.4 PSYCHOLOGICAL DYSFUNCTION FOLLOWING ACLR

Following ACLR, psychological dysfunction is common and often plays a large role in an individual’s decision to resume sport-related activities. (Gobbi and Francisco 2006, Ardern and Kvist 2015, Bien and Dubuque 2015, Dingenen and Gokeler 2017, Burland, Toonstra et al. 2018) More importantly, psychological dysfunction that goes unaddressed after ACLR has the potential, in conjunction with other suboptimal physical outcomes, to promote increased disability. (Kvist, Ek et al. 2005, Pietrosimone, Lepley et
al. 2013, Christino, Fantry et al. 2015, Lentz, Zeppieri et al. 2015, Lepley 2015) It is therefore essential to recognize and understand the consequences of prolonged psychological dysfunction in order to provide comprehensive and effective treatment for individuals who undergo ACLR.

5.5 Established Psychological Barriers after ACLR

Psychological factors experienced by athletes after major joint injuries may include anger, anxiety, depression, (Morrey, Stuart et al. 1999) kinesiophobia, fear of reinjury, or lack of confidence. (Ardern and Kvist 2015) Importantly, there is a growing body of evidence to suggest that these psychological factors may be modifiable through behavioral and cognitive therapies. (Everhart, Best et al. 2013, Ardern 2015) Recent systematic reviews report that positive psychological responses (i.e. confidence, self-efficacy, optimism, increased motivation, lower fear) increase the likelihood of returning to active lifestyles and sport participation. (Everhart, Best et al. 2013, Feller and Webster 2013, te Wierike, van der Sluis et al. 2013) It is likely that individual variations in psychological responses are a consequence of differing appraisals and perceptions of injury and of their physical capability. (Ardern 2015) In fact, those who feel they will not be successful in completing a specific task, or believe they will fail at returning to preinjury levels of activity, may demonstrate self-limiting tendencies. (Podlog and Eklund 2005, Ardern 2015, Burland, Toonstra et al. 2018) The literature also demonstrates a consistent relationship between higher levels of self-confidence, optimism and motivation, and subsequently successful return to sport following ACLR. (Gobbi and Francisco 2006, Everhart, Best et al. 2013) Recognition of these psychological
characteristics has clinical implications as it may identify areas where targeted interventions can be implemented to mitigate poor outcomes.

Various theoretical models have been proposed within the context of ACLR to help clinicians understand psychological constructs affecting recovery. Each model has been developed to incorporate commonly reported themes, such as fear, hesitation, depression, kinesiophobia, etc. (Tjong, Murnaghan et al. 2014, Burland, Toonstra et al. 2018) In particular, the literature points to three basic psychological theories helping to organize these constructs: 1.) fear-avoidance model, 2.) self-efficacy theory, and 3.) stress, health and lack of social support hypothesis.

The fear-avoidance model is a cognitive-behavioral theory, where constructs of fear of re-injury, pain catastrophizing and kinesiophobia arise from associating certain movements with pain or subsequent injury.(Vlaeyen and Linton 2000, Leeuw, Goossens et al. 2007) Constructs associated with fear-avoidance behaviors are common psychological responses throughout recovery, especially considering that pain is a regularly reported impairment following ACLR.(Chmielewski, Jones et al. 2008, Wiese-Bjornstal 2010, Flanigan, Everhart et al. 2013, te Wierike, van der Sluis et al. 2013) In fact, fear of re-injury has been cited as one of the key factors predicting failure to return to pre-injury sport after ACLR.(Ardern 2015) Individuals after ACLR with elevated fear of re-injury also commonly report kinesiophobia, as these individuals often demonstrate avoidance of specific movements or behaviors due to their inescapable fear of sustaining another injury.(Flanigan, Everhart et al. 2013, Tichonova, Rimdeikiene et al. 2016) Pain catastrophizing is an additional construct of this model that deals with exaggerated negative psychological responses to painful stimuli, or even the
anticipation of pain. Pain catastrophizing can impede recovery by causing avoidance of activities due to fear of recurring pain (i.e., kinesiophobia), or guarding behaviors that result in abnormal compensatory movement strategies. (Tichonova, Rimdeikiene et al. 2016)

Fear-avoidance behaviors are typically viewed as the result of pain sensation or perception following ACLR. However, pain can also contribute to expectations of perceived failure, specifically pointing to the theory of self-efficacy. (Kvist, Ek et al. 2005, George, Lentz et al. 2012) The theory of self-efficacy deals with an individual's perception of their capability to complete a task, and also has the potential to play a role in recovery. (Thomeé, Währborg et al. 2007, Chmielewski, Zeppieri et al. 2011, te Wierike, van der Sluis et al. 2013) Athletes who report higher levels of self-efficacy have a greater likelihood of returning to sport following ACLR and have shown increased motivation, (Thomeé, Währborg et al. 2007, Brand and Nyland 2009) improved physical activity, and fewer knee symptoms one year following ACLR. (Thomeé, Währborg et al. 2008, te Wierike, van der Sluis et al. 2013) Patients with greater self-efficacy (positive self-talk, setting goals, higher motivation) are also more compliant and demonstrate greater effort with therapeutic exercises, increasing their likelihood to observe beneficial gains following rehabilitation. (Brewer, Van Raalte et al. 2000, Scherzer, Brewer et al. 2001)

The last theoretical model related to the hypothesis of stress, health and lack of social support centers around psychological stress and its influence on global outcomes, including mental and physical health. Self-identity is very important to this model, stating that social support, or even perceived support from others (i.e.
teammates, coaches, etc.), can positively influence psychological and physical outcomes following injury. Although not a direct construct of this model, clinical depression has been reported as a significant comorbidity in ACLR populations and deals with abnormal psychological stress in dealing with the injury. Strikingly, Garcia et al (Garcia, Wu et al. 2016) reported that the incidence of depression may be upwards of 42% in those undergoing ACLR, and others have supported the notion that ACLR patients experience higher rates of depression compared to the US average. (Wu, Liu et al. 2016) Depression has a negative effect on physiological outcomes after ACLR, with patients who exhibit greater depressive symptomology also demonstrating lower self-reported knee function. Appropriate identification of the symptoms of clinical depression should be an important part of initial patient evaluation in order to assist in the restoration of optimal mental and physical health.

Historically, negative psychological function has been thought to be the result of an ACL injury; however, it is also important to contextualize the point that psychological differences may also be a predisposing factor to ACL injury. To this point, Swanik et al (Swanik, Covassin et al. 2007) have found that poor neurocognitive function (defined as verbal and visual memory, processing speed and reaction time) is a characteristic among intercollegiate athletes who subsequently experience an ACL injury. Nevertheless, psychological dysfunction is common in patients recovering from ACLR, whether it is present before or after the injury, and addressing these psychological alterations during the rehabilitation phase would be beneficial for improving overall outcomes and quality of life in these patients.
5.6 Learned Helplessness: A Motor and Behavioral Deficit after Neural Compromise

Distinctly different to the established psychological barriers after ACLR that typically deal directly with pain or mental health, LH is a maladaptive motor and behavioral deficit in response to neural compromise. (Salomons, Moayedi et al. 2012) LH has previously been well-established in populations with neural impairments, such as patients after stroke, traumatic brain injuries, and deafferentation. Though individuals undergoing ACLR have not traditionally been viewed as a neurally compromised population, emerging evidence clearly demonstrates that following both ACL injury and reconstruction, disruption of mechanoreceptors in the knee joint along with concomitant pain and swelling lead to altered afferent signaling from the joint, ultimately leading to motor inhibition. (Pietrosimone, McLeod et al. 2012) Immediate loss of quadriceps function post-surgery, and changes in brain activation and excitability, support the tenet that ACLR individuals have systemic neural impairments. (Needle, Lepley et al. 2017) In order to fully understand LH as a construct that is present in patients with ACLR, it is important to appreciate the neural impairments that are present in this population, in conjunction with the psychological constructs that are detailed in section 5.1.

5.7 NEURAL ALTERATIONS AND PSYCHOLOGICAL DYSFUNCTION

5.8 An Overview of Neural Alterations After ACLR

Neural alterations are a common consequence of ACL injury and ACLR, and often present clinically as persistent quadriceps muscle weakness. (Palmieri-Smith, Thomas et al. 2008, Hart, Pietrosimone et al. 2010) Despite no direct injury to the
muscle fibers or innervating nerve, patients often demonstrate significant difficulty initiating and sustaining a full quadriceps contraction. (Stokes and Young 1984, Hopkins and Ingersoll 2000) Although this muscle inhibition has been previously suggested as an initially protective mechanism, prolonged quadriceps inhibition may lead to poorer health. (Becker, Berth et al. 2004) Peripheral disruption of mechanoreceptors in the ACL, along with concomitant joint swelling and pain, can cause abnormal afferent signaling to the spinal cord and supra-spinal centers, thus resulting in poor efferent signaling to the quadriceps and ultimately quadriceps inhibition. (Ingersoll, Grindstaff et al. 2008, Palmieri-Smith, Thomas et al. 2008, Palmieri-Smith and Thomas 2009, Harkey, Luc-Harkey et al. 2016) Alterations in the excitability of motor generating pathways, namely the spinal-reflexive (Pietrosimone, Lepley et al. 2015) and corticospinal pathways, (Heroux and Tremblay 2006, Norte, Pietrosimone et al. 2010, Pietrosimone, Lepley et al. 2013, Lepley, Ericksen et al. 2014, Lepley, Bahhur et al. 2015) are large components of both acute and persistent quadriceps weakness after ACLR. Existing literature demonstrates that ACLR individuals who were on average 2-years post-operative exhibited larger alterations in neural activity, specifically depressed corticospinal excitability to the quadriceps muscle group compared to healthy controls. (Lepley, Ericksen et al. 2014, Pietrosimone, Lepley et al. 2015) Emerging hypotheses regarding the underlying contributor to long-term alterations in corticospinal excitability propose that in order to compensate for the presence of altered peripheral input, cortical reorganization and brain neuroplasticity occurs, and these plastic changes may be responsible for the chronic motor impairments observed years after

5.9 Foundational Evidence from Neuroscience: A Proposed Translation of Neural Alterations to the ACLR Patient

To date, the interactions between nervous system alterations and psychological factors has yet to be investigated in an ACLR population. Furthermore, evidence for this relationship has only been established in classic neural injury populations (i.e. stroke, traumatic brain injuries, deafferentation). (Maier 1976, Sterr, Freivogel et al. 2002, Salomons, Moayedi et al. 2012) Theories regarding psychological adaptations suggest that following neural insult and contraction of the damaged cortical region, generating movement patterns of the involved extremity may be difficult or painful, thus resulting in less desire to utilize the injured limb and eventually a learned suppression of movement, increased disability, and psychological deficits associated with extremity use. (Taub, Uswatte et al. 2006) Compensatory limb use, or disuse of the affected limb, has been established in humans as an inability to generate movements and psychological distress occurring following neural insult after stroke. (Taub, Uswatte et al. 2003, Nakling, Aarsland et al. 2017) Disuse of the damaged limb may be promoted due to increased difficulty with movement from the loss of neural input and, secondarily, because of learned compensatory use of the non-affected limb. (Schallert, Leasure et al. 2000, Taub, Uswatte et al. 2006) Motor control reorganization and behavioral adaptations are highly based on learning and experience, demonstrating the importance of understanding how cortical alterations have the potential to modulate behavior and psychological well-being. (Liepert, Miltner et al. 1998, Taub, Uswatte et al. 2003,
Although patients recovering from ACLR are not often viewed as a neurologically impaired population, emerging literature in ACLR cohorts suggests that these individuals are in fact neurologically impaired, with reorganization of central nervous system function. (Pietrosimone, McLeod et al. 2012, Grooms, Page et al. 2017, Needle, Lepley et al. 2017) Specifically, ACLR patients experience deficiencies in the reflexive control of their quadriceps muscle (Stokes and Young 1984, Hopkins and Ingersoll 2000), deficits in their ability to detect sensory stimuli from the knee at the somatosensory cortex (Needle, Lepley et al. 2017), and decreased motor output from the primary motor cortices of each hemisphere (areas specifically responsible for thigh muscle innervation) (Lepley, Bahhur et al. 2015, Pietrosimone, Lepley et al. 2015), ultimately resulting in muscle weakness from a neural inability to adequately contract muscle during activity. (Pietrosimone, Lepley et al. 2013) Notably, these nervous system changes after ACLR have the potential to alter both physical and psychological function.

5.10 Conceptual Framework for Neural Alterations that May Impair Psychological Function

In sections 5.5, 5.6 and 5.7, both neural alterations and psychological deficits are highlighted as common impairments observed after ACLR. Using a preliminary, theoretical framework, we believe that together, these factors have the potential to interact and negatively influence post-operative outcomes. Neural alterations are common after ACL injury and play an important role in regaining optimal physical function. (Pietrosimone, McLeod et al. 2012) Previous data suggest that neuroplasticity of the motor cortex may develop as a chronic adaptation to ACL injury and ACLR,
where early changes in spinal-reflexive and peripheral neural activity initiate a
reorganization within the brain to compensate for decreased excitability. (Lepley, Gribble
et al. 2015, Needle, Lepley et al. 2017) Neural changes, specifically to the motor cortex,
have been proposed to occur as early as 3-6 months after ACLR, and we therefore
speculate that LH would most likely arise during the time when brain neuroplasticity
occurs. (Grooms, Page et al. 2017) Psychological factors (such as fear avoidance
behaviors) arising after ACLR have also been identified as potential contributors
towards negative post-operative outcomes. (Kvist, Ek et al. 2005, George, Valencia et al.
2010, Everhart, Best et al. 2013) These factors are frequently correlated with deficits in
quadriiceps strength (Lepley and Palmieri-Smith 2015, Burland, Kostyun et al. 2018) and
often influence return to sport status. (Ardern, Taylor et al. 2013) As the relationships
between post-operative outcomes are dynamic in nature, we hypothesize that LH may
arise after ACLR in one of two ways. First an individual’s inability to successfully
execute a task, due in part to neural inhibition, influences a variety of clinical outcomes
and fosters an environment of uncontrollability, leading to the development of LH and
further exacerbating the negative cyclical relationship between post-operative
outcomes. Secondly, protracted changes in neural activity lead to distinct whole-brain
neuronal changes that can directly influence brain regions devoted to processing of
emotional responses that are associated with LH (Figure 5.1). (Salomons, Moayedi et al.
2012, Kim, Perova et al. 2016) Here we present the initial LH theoretical framework
proposing a new direct link between depressed neural activity and psychological
dysfunction after ACLR using foundational evidence from neuroscience and psychology
disciplines to support the integration of this concept into recovery.
Figure 5.1 illustrates a theoretical LH hypothesis where persistent neural alterations arising after ACLR initiate a maladaptive LH psychological response and foster a cycle of negative post-surgical outcomes. The model depicts that patients experience alterations in afferent neural drive due to loss of mechanoreception, pain, and swelling following ACL injury and ACLR, leading to subsequent alterations in central nervous system neural activity. This change in neural activity can either acutely foster an environment of uncontrollability promoting LH or persist, leading to a cyclical pattern of muscle inhibition and weakness, altered joint biomechanics, depressed self-reported and psychological function that generates the construct of LH in these patients; conversely, the change in neural activity can be restored, placing patients on the path to more positive outcomes. The negative psychological responses that ensue likely can further exacerbate the negative neural responses, creating a cyclical pattern that results in decreased overall quality of life in these patients.
While research on self-reported and psychological function after ACLR has rapidly expanded over the past several years, (Tjong, Murnaghan et al. 2014, Lepley and Palmieri-Smith 2015, Pietrosimone, Lepley et al. 2016, Burland, Toonstra et al. 2018, Lepley, Pietrosimone et al. 2018) there is still limited information on whether neurally mediated psychological function is a limiting factor in regaining optimal post-operative
function. In support of our model, preliminary data from our laboratory demonstrate that in a cohort of 10 ACLR individuals (on average 5 years after ACLR), reduced signaling from the motor cortex to the quadriceps muscle is related to greater LH ($r=0.694$, $p=0.018$). LH was measured using a validated subjective scale (Electronic Supplementary Material Appendix B)(Quinless and Nelson 1988) and corticospinal excitability, specifically motor evoked potentials, were obtained using transcranial magnetic stimulation as described previously by Lepley et al.(Lepley, Bahhur et al. 2015, Lepley, Gribble et al. 2015) These data are the first to indicate that individuals who perceive themselves to be more helpless demonstrate reduced neural signaling to the muscle. Additionally, using a modified validated Arthritis Helplessness Index (Electronic Supplementary Material Appendix C)(Nicassio, Wallston et al. 1985) that uses language and terms specific to ACL injuries, greater self-reported helplessness was associated with lower peak knee flexion angles during a jump-landing task ($r=0.673$, $p=0.03$) in the same 10 ACLR individuals, thus demonstrating that individuals who perceive themselves as more helpless also exhibit less optimal knee joint biomechanics. Due to the pilot nature of this work, we caution the reader against inferring causality, and emphasize that we are presenting a preliminary link between these variables, not a cause and effect analysis. Collectively, however, these preliminary data indicate a direct link between neural deficits and psychological dysfunction following ACLR, warranting further research into this area.

5.11 STRATEGIES TO ENHANCE RECOVERY AFTER ACLR: A CALL TO ACTION

After ACLR, conventional case management often includes strategies that inherently, although not intentionally, promote decreased activity, inhibition and atrophy
of the quadriceps (e.g. peripheral nerve blocks for pain control, movement and weight-bearing restrictions).\cite{kvist2004, failla2015, swank2017} Additionally, rehabilitation efforts aimed at reducing psychological distress are lacking.\cite{ardern2015, christino2015} Collectively, these management and treatment strategies have the potential to unknowingly prolong dysfunction after ACLR. For instance, muscle weakness due to decreased limb use or avoidance following injury may increase LH behaviors.\cite{klein1976, taub1994, taub2006} Continued improper utilization of the injured extremity initiates compensatory learned motor patterns when executing motor tasks. Ultimately, this pattern of helplessness, continued disuse, and poor movement control impedes an individual’s ability to function appropriately and often negatively influences overall quality of life. Therefore, we believe that after ACLR, there may be a negative cyclical relationship between important post-operative outcomes (i.e. decreased strength, altered biomechanics, self-reported disability [Figure 5.1]) and that these outcomes may be further influenced and perpetuated by LH type behaviors. Since this is the first proposal of this theoretical model, it remains unclear what attributes contribute to a patient following the more positive path depicted in Figure 5.1. Although all ACLR participants experience a disruption in afferent neural signaling from the joint due to the inherent loss of mechanoreceptors that were in the once intact ACL, we speculate that individuals after ACL injury and ACLR experience LH changes on a sliding, continuous scale. It is likely that individuals with greater deficits in neural activity, or who experience a longer recovery from these deficits, will demonstrate more severe symptoms (weakness, atrophy, altered mechanics etc.) and thus also report feeling
worse and exhibit more psychological dysfunction and self-reported disability. There also lies the potential for sports medicine clinicians to intervene and help the patient along the more positive path with novel therapeutic interventions, which are outlined in the next section.

### 5.12 Treatment Considerations

Several therapies may help to provide clinicians with a starting point for mitigating neural alterations that precipitate LH after injury. Following the identification of LH behavior, Taub (Taub, Uswatte et al. 2006) and colleagues were the first to theorize that through the use of targeted training of the impaired limb in adult monkeys, use of the impaired limb could be restored. They referred to this training phenomenon as constraint-induced movement therapy where the healthy/uninjured limb was restrained to condition the animal to utilize the impaired extremity. (Taub, Crago et al. 1994, Taub, Uswatte et al. 2003) Evidence in support of constraint-induced movement therapy demonstrates that reorganization of motor maps can occur through rehabilitative training specific to the impaired limb. (Liepert, Miltner et al. 1998, Taub, Uswatte et al. 2003) Although constraint induced movement therapy has been suggested as a therapy beneficial to retraining injured extremities, its applicability to the ACLR population may be limited, as immediately post-operation, extensive exercising of the involved limb is contraindicated. However, emerging evidence highlights the use of eccentric cross-exercise (aggressively exercising the uninvolved limb to initiate strength and neural benefits to the injured limb (Taub, Uswatte et al. 2003, Taub, Uswatte et al. 2006, Lepley, Grooms et al. 2018)) training during scenarios where conventional training of the involved limb is contraindicated, such as acute post-surgical stages after
Eccentric cross-exercise training regimens promote muscle strength through improving alpha motor neuron pool recruitment and firing rate in the non-exercised limb. (Lepley and Palmieri-Smith 2014) This principle of eccentric cross-exercise is applicable after joint injury, such as ACL injury, for those who cannot exercise the injured or reconstructed limb. Of particular interest is the ability for eccentric cross-exercise to improve central neural mechanisms. (Carr, Harrison et al. 1994, Kidgell, Frazer et al. 2015) Importantly, this type of therapy promotes benefits in both strength and neural function, providing clinicians with the potential to improve numerous rehabilitation components. Also, as strength has been linked with self-reported function after ACLR (Pietrosimone, Lepley et al. 2016, Burland, Kostyun et al. 2018, Lepley, Pietrosimone et al. 2018), there is also potential for therapies targeting neural function and strength to also improve components of psychological function, likely improving perceived ability, or decreasing helpless type behaviors. For instance, disinhibitory modalities such as transcutaneous electrical nerve stimulation have been shown to improve patient outcomes, specifically voluntary quadriceps activation after ACLR. (Harkey, Gribble et al. 2014) The overlap between neural alterations and psychological dysfunction in clinical neuroscience demonstrates the feasibility of targeting neural impairments and also improving psychological function. (Taub, Crago et al. 1994, Liepert, Miltner et al. 1998, Taub, Uswatte et al. 2003, Taub, Uswatte et al. 2006, Shumway-Cook and Woollacott 2012) For instance, improving a patient’s ability to voluntarily recruit muscle via disinhibitory modalities during therapeutic rehabilitation
will enable that patient to effectively perform the task given, directly resulting in psychological benefits. Hence, disinhibitory modalities (Harkey, Gribble et al. 2014), including transcutaneous electrical nerve stimulation and neuromuscular electrical stimulation should also be considered in rehabilitation to improve neuromuscular function.

Another innovative and emerging therapeutic intervention that has the potential to improve central nervous system function and directly improve patient outcomes is transcranial direct current stimulation (tDCS). tDCS, a non-invasive brain stimulation intervention, has been shown to be effective in reducing pain and improving physical function in individuals with knee osteoarthritis. (Chang, Bennell et al. 2017) Additionally tDCS has not only been shown to increase cortical excitability (Nitsche and Paulus 2000), but also has implications for treating depressive symptoms, which makes it a marketable treatment option for individuals who may be experiencing both psychological and neural dysfunction. (Nitsche, Boggio et al. 2009)

Practical applications for mitigating psychological behaviors associated with LH entail the use of interventions targeted at improving an individual’s perception that their ‘failure’ can be overcome by their effort. (Stipek and Kowalski 1989) Specifically, this means emphasizing ‘learning goals’ related to task completion (i.e. increasing ability over time) versus simply executing ‘performance’ related goals (i.e. adequacy of ability to perform). Previous research has demonstrated that children who were given instructions focusing strictly on ‘performance’ performed worse and demonstrated more helplessness compared to those who were instructed to focus simply on task completion (i.e. learning the task). (Elliott and Dweck 1988, Stipek and Kowalski 1989)
Strategies that de-emphasize ‘evaluation’ of the assigned task are thought to improve an individual’s self-perceived ability. (Stipek and Kowalski 1989) If these notions regarding overcoming LH are applied to rehabilitation after ACLR, it is plausible that creating a rehabilitation environment that does not solely evaluate success or failure on specific tasks, but utilizes learning objectives and small, attainable goals, may help to promote successful mastery-oriented response to common obstacles faced during recovery. (Diener and Dweck 1980, Elliott and Dweck 1988) Additionally, cognitive behavioral therapies such as imagery, mindfulness, guided relaxation and breathing techniques (Cupal and Brewer 2001, Mendonza, Patel et al. 2007) could also be used to improve psychological well-being. Early use of such behavioral therapies and focus on bolstering psychological function during rehabilitation may help to alleviate psychological distress and reduce the risk of developing maladaptive behaviors often associated with recovery after ACLR. (Chmielewski, Zeppieri et al. 2011) Behavioral therapies aimed at mitigating LH combined with disinhibitory neural modalities have the potential to improve both neuromuscular and psychological function after ACLR.

5.13 CONCLUSION

The evidence summarized in this theoretical framework demonstrates the potential for nervous system alterations to promote LH after ACLR. A natural extension of our need to comprehensively care for the patient after ACLR is to consider psychological health during ACL rehabilitation, recognize LH as a potential barrier to successful recovery, and study future interventions capable of mitigating this modifiable factor.
CHAPTER 6. Examining the influence of neuroplasticity on learned helplessness after ACLR: early versus late recovery

A manuscript based on the research presented in this chapter has been submitted for publication:

Burland JP, Lepley AS, Cormier M, DiStefano LJ, Lepley LK. (Submitted to.) Sport Health.

6.1 ABSTRACT

Background: Altered neural signaling is known to have a direct impact on psychological wellness. It is plausible that these environments may interact after anterior cruciate ligament reconstruction (ACLR), in some cases manifesting as a condition known as learned helplessness (LH). LH is a psychological paradigm that can clinically manifest as altered neuromuscular control strategies, reduced motivation and greater psychological deficits. To better understand the interactions between complex neural and psychological environments, we sought to evaluate the relationship between LH, neural activity and quadriceps function in both early and late ACLR populations.

Methods: Twenty-nine individuals with unilateral ACLR were categorized into early ACLR (<2 years, age:19.13±2.18y; height:1.77±0.11m; mass:76.903±11.87kg) or late ACLR (>2 years, age:22±23y; height:1.67±0.07m; mass:65.66±11.33kg). Quadriceps function (activation and strength), spinal-reflexive and corticospinal excitability (active motor thresholds [AMT], motor evoked potential [MEP], and LH were obtained. A principal component analysis (PCA) was performed by ACLR group (early, late) to identify which factors of helplessness were most associated with neural activity and quadriceps function. Pearson product moment correlation analyses were then
performed by group to determine the associations between individual components and main outcomes. **Findings:** In the early ACLR group, cognitive readiness was moderately associated averaged normalized MVIC of the ACL limb ($r^2=0.513$, $p=0.004$) and self-awareness/management was moderately and negatively associated with AMT of the ACL limb ($r^2=0.238$, $p=0.05$). In the late ACLR group intrinsic helplessness was associated with MEP:M at 120% of AMT in ACL limb ($r^2=0.653$ $p=0.005$).

**Interpretation:** Learned helplessness is made up of several attributional constructs which are altered at different phases of recovery after ACLR. LH constructs interact differently with neural activity and quadriceps function across time. Targeting cognitive readiness when completing physical tasks, being more self-aware and able to self-manage may promote better function early on in recovery. Establishing learning-oriented goals versus mastery type goals throughout recovery may reduce greater intrinsic helplessness in patients further removed from surgery. **Word Count: 312**

### 6.2 INTRODUCTION

Protracted deficits in knee function after anterior cruciate ligament reconstruction (ACLR) are commonly attributed to the extensive neural alterations that are overserved after injury.(Lepley, Gribble et al. 2015, Lepley and Palmieri-Smith 2015, Otzel, Chow et al. 2015, Pietrosimone, Lepley et al. 2015) Notably, these wide-spread neural impairments impede the ability of targeted exercises to efficiently strengthen the quadriceps muscle both acutely and well into the chronic phases of recovery.(Pietrosimone, Lepley et al. 2015, Needle, Lepley et al. 2017) Quadriceps activation deficits are thought to directly contribute to quadriceps weakness through spinal and cortically driven mechanisms. Rising awareness suggests that the presence
of altered peripheral input from the knee joint and changes in reflexive alterations lead to cortical reorganization and neuroplasticity.

Altered neural signaling is known to have a direct impact on psychological wellness. (Johnson, Paranjape et al. 2011, Nakling, Aarsland et al. 2017) (Taub, Uswatte et al. 2006) Specific to ACLR, psychological dysfunction is a rapidly growing area of interest and so far, data has demonstrated that psychological wellness is highly associated with physical outcomes. Given the basic mechanistic data to support the inherent link between neural signaling and psychological function (Maier 1976, Taub, Uswatte et al. 2006, Salomons, Moayedi et al. 2012), we believe these environments may interact after ACLR and in some cases, manifest as a condition known as learned helplessness (LH). (Salomons, Moayedi et al. 2012) LH is a psychological paradigm that has been well demonstrated in both animal and chronic disease literature (Taub, Uswatte et al. 2006, Salomons, Moayedi et al. 2012, Kim, Perova et al. 2016) in response to traumatic injury, neural impairments, and uncontrollable situations. LH can clinically manifest as altered neuromuscular control strategies, reduced motivation and greater psychological deficits. (Klein, Fencil-Morse et al. 1976, Samwel, Evers et al. 2006, Salomons, Moayedi et al. 2012) Although LH is a well-documented clinical manifestation in classic populations with neural insults, the application of LH to an ACLR population is a novel concept. Recently, a theoretical framework (Burland, Lepley et al. 2019) has proposed that neural impairments, occurring as a consequence of ACL injury and ACLR, have the ability to initiate a maladaptive LH psychological response, fueling a negative cyclical relationship between common post-surgical outcomes. In support of this concept, preliminary evidence suggests that in patients who are greater
than 2 years removed from ACLR, reduced neural signaling (via motor cortex pathways) to the quadriceps muscle is associated with greater perceived helplessness measured using a self-reported LH outcome. (Burland, Lepley et al. 2019)

To further understand LH and the impact this condition may have on recovery, we sought to evaluate the presence of LH in a cohort of patients after ACLR. As LH is a complex and multifactorial neurocognitive construct, we wanted to explore whether specific helplessness constructs differ between patients who are less than 2 years (early) and more than 2 years (late) after ACLR. Secondly, we sought to further elucidate whether these underlying LH constructs interact with neural excitability and quadriceps function differently between early and late ACLR groups. We are motivated to do this to better understand the barriers to recovery and the potential for the complex neural and psychological environments to interact and drive persistent dysfunction. Thus, the purpose of this study was to evaluate the relationship between self-reported LH, neural activity (spinal-reflexive, corticospinal excitability) and quadriceps function (strength and activation) in both early and late ACLR populations.

6.3 METHODS

Patients

Twenty-nine patients who had sustained a primary, unilateral ACL rupture and subsequently underwent ACLR were recruited from a single orthopaedic surgeon through the University of XXXX Department of Orthopaedic Surgery and the general student population. All patient demographics can be found in Table 1. Patients were excluded if they had a previous history of knee surgery other than the current ACLR, sustained a contralateral lower extremity injury within the past 6 months, had a history
of seizures or concussion in the past 6 months, and if they had a past medical diagnosis of cancer under areas where magnetic or electrical stimulation would be conducted. Written and informed consent was obtained, and all procedures were approved the University’s institutional review board.

Protocol

All patients included in this study reported to the University of XXX University of XXXX, XXXX and XXXX Laboratory for a single cross-sectional test session where patients underwent neural excitability and quadriceps function testing and completed a self-reported LH outcome measure. Spinal-reflexive excitability, corticospinal excitability and quadriceps function (strength and activation) were collected bilaterally during a single test session. Self-reported learned helplessness was evaluated using a validated learned helplessness outcome measure. (Nicassio, Wallston et al. 1985, Brady 2003)

**Quadriceps spinal-reflex excitability**

Quadriceps spinal-reflex excitability was quantified using the Hoffmann reflex (H-reflex) normalized to maximal muscle responses (H:M), as previously published. (Hopkins, Ingersoll et al. 2001, Palmieri, Tom et al. 2004, Lepley, Gribble et al. 2015) Quadriceps H-reflex is an electrically induced physiological equivalent to the stretch reflex and is a representation of the ability to recruit the quadriceps muscle through reflexive means. (Rosenthal, Moore et al. 2009, Hart, Pietrosimone et al. 2010) During testing, patients were positioned supine with their knee’s slightly flexed (~10-15 degrees) using a pillow. Collection sites and recording electrode were shaved (when necessary) and debrided and cleaned with alcohol prior to data collection. Two 10 mm, pregelled Ag-AgCl (EL503, BIOPAC Systems Inc., Goleta, CA, USA) disc-shaped
Surface electromyographic (EMG) electrodes were positioned 1.75 cm apart over the quadriceps muscle belly. (Palmieri and Ingersoll 2005) EMG signals were band-pass filtered from 10 to 50 Hz and collected at 1024 Hz with a common-mode-rejection ratio of 110 dB. A 2 mm shielded disc stimulating electrode (EL252RT, BIOPAC Systems Inc.) was placed over the femoral nerve. A round, self-adhesive dispersive electrode was positioned over the ipsilateral hamstring muscle belly. A 1 ms square wave stimulus produced with a BIOPAC stimulator module (STM100C, BIOPAC Systems, Inc.) and a 200 volt maximum stimulus adaptor (STMISOC, BIOPAC Systems Inc) was delivered to the femoral nerve. (Hopkins, Ingersoll et al. 2001) The stimulus was increased until a maximum H-reflex was elicited and visualized, and then three maximal H-reflexes were collected at that voltage. The stimulus was increased until a maximal muscle response (M-response) was elicited, in which three maximal M-responses were elicited. The average peak to peak values of the three H-reflexes were normalized to the average peak to peak values of the three M-responses (H:M ratio).

**Quadriceps corticospinal excitability**

Transcranial magnetic stimulation (TMS) was used to determine the active motor thresholds (AMT) and amplitude of motor evoked potentials (MEP) elicited at 120% of AMT. Two 10 mm EMG electrodes were positioned in the same manner as during spinal-reflex excitability testing. Debridement and cleaning of the collection and recording electrode site was also performed as needed. Subjects were seated in a testing chair (MagVenture Treatment Chair, 9016B008 MagVenture Inc., Atlanta, GA) and muscle force was monitored using a handheld dynamometer (micro FET; Hoggann Scientific LLC, West Jordan UT). A Lycra swim cap, with a 0.5 cm grid, was positioned
on the subjects head by using straight lines drawn vertically in the sagittal (center of the occiput to the nose) and frontal planes (connecting each external auditory meatus) allowing for identification of the approximate motor cortex location. (Norte, Pietrosimone et al. 2010, Lepley, Gribble et al. 2015) A double cone angled TMS coil (D-B80, MagVenture Inc., Atlanta, GA) was positioned over the intersected lines and moved in increments of 0.5 cm in anterior-to-posterior and medial-to-lateral directions until the optimal stimulating point was detected; defined as the location producing the greatest MEP amplitude in the quadriceps. (Livingston and Ingersoll 2008) The stimulator (MagPro R30 with Magoption, MagVenture Inc.) was secured over that spot using a flexible mount (Pietrosimone and Gribble 2012) (Super Flex Arm, MagVenture Inc.). AMT was determined once the optimal stimulating point was located. The AMT is defined as the lowest TMS intensity required to evoke a measurable (>100 μV) MEP in five out of 10 trials. (Pietrosimone, Lepley et al. 2013, Lepley, Gribble et al. 2015) Once the AMT was established, five MEPs were elicited at 120% of AMT. Five peak-to-peak MEP amplitude values were averaged and normalized to the average of three maximal muscle responses elicited during H-reflex excitability testing. (Groppa, Oliviero et al. 2012, Lepley, Ericksen et al. 2014, Lepley, Gribble et al. 2015)

**Quadriceps Strength**

Quadriceps maximum voluntary isometric contraction (MVIC) was used to assess quadriceps muscle strength. Patients were seated in a Biodex System IV Pro Dynamometer (Biodex Medical Systems, Shirley, New York, USA) with their knee and trunk in 90° of flexion. (Pietrosimone, Hammill et al. 2008, Pietrosimone, Hart et al. 2009, Pietrosimone and Ingersoll 2009) Restrictive straps were secured at the lap and over
the trunk to control accessory movement during the maximum effort knee extension task. The distal tibia was secured to a pad on the arm of the dynamometer with Velcro straps. Patients were instructed to grab the hand holds on the side of the dynamometer during all contractions to avoid unwanted upper extremity involvement. (Pietrosimone, Hammill et al. 2008, Pietrosimone, Hart et al. 2009, Pietrosimone and Ingersoll 2009) Patients were asked to perform several practice MVICs to ensure that maximal effort was being given. Patients performed three MVICs with visual feedback and verbal encouragement with 60 seconds between trials. Quadriceps isometric MVIC were obtained bilaterally and normalized to body mass (Nm/kg) for analysis. 

**Quadriceps Activation**

Immediately following MVIC testing, two 7x13cm self-adhesive stimulating electrodes were placed on the proximal vastus lateralis and distal vastus medialis. (Pietrosimone, Hammill et al. 2008, Pietrosimone, Hart et al. 2009, Pietrosimone and Ingersoll 2009) A custom program (LabView, National Instruments, Austin, TX) was used to automatically trigger 150 volts of electrical stimulation (100ms train of 10 stimuli, at 100 pps, with a pulse duration of 600 µs, and a 0.01 ms pulse delay via the Grass S48 dual channel electrical stimulation unit with an SIU8T isolation unit attached [Grass Products, Natus Neurology]) to the quadriceps muscle, contracting any muscle not voluntarily recruited. To quantify quadriceps activation failure the central activation ratio (CAR) was calculated (Equation 1). Equation 1: Central Activation Ratio =MVIC/MVIC + Superimposed Burst. A CAR of 1.00 was utilized to represent complete quadriceps activation. (Barber, Noyes et al. 1990) Quadriceps activation was obtained bilaterally.
Learned helplessness

In order to quantify self-reported LH, patients completed a validated Arthritis Helplessness Index (AHI). (Nicassio, Wallston et al. 1985, Brady 2003) The AHI is a 15-question survey that was modified to change language regarding arthritis to wording associated with ACL injury (e.g. the original question would have read “My [arthritis] is controlling my life” and was modified to “My [ACL injury] is controlling my life”). (Burland, Lepley et al. 2019) This was done to help identify and assess perceptions of helplessness specific to knee injuries and was renamed the ACL helplessness index (ACL-HI) for the purpose of this study. Higher scores on the scale are indicative of greater amounts of helplessness.

Statistical Analyses

ACLR patients were categorized into 1 of 2 groups prior to statistical analysis: ACLR individuals who were less than 2 years removed from surgery (average time from surgery 0.80 ± 0.32 years) were categorized as “early” and those who were greater than or equal to 2 years removed from surgery (average time from surgery 5.70 ± 2.06 years) were categorized as “late”. Group differences were evaluated using independent t tests (Table 1). As LH is a complex psychological condition, we performed a principal component analysis (PCA) by ACLR group (early, late) to identify which factors of helplessness were most associated with neural activity and quadriceps function. Following the PCA, individual components (Table 2 and 3) that emerged were given an overarching “name” which represented the questions that were highly loaded within that component. Component names were validated by a blinded qualitative researcher (SM). Components that were loaded and ranged between 0.4 and 1 were considered strong
and were retained for further analyses. (Cohen, Cohen et al. 2003) Pearson product moment correlation analyses were then performed by group to determine the associations between individual components that emerged from the PCA and neural excitability and quadriceps function. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) software version 24.0 (IBM Corp., Armonk, NY, USA) and α-level was set a priori at $P \leq 0.05$.

6.4 RESULTS

Patient demographic variables means and standard deviations for all outcome measures for the early and late ACLR groups can be found in Table 1. The results of the PCA and correlation analyses are presented by ACLR group in the following subsections.
Table 6.1. Patient demographics

<table>
<thead>
<tr>
<th>Outcome variable</th>
<th>Mean ± SD</th>
<th>Early ACLR 15 (9 males, 7 females)</th>
<th>Late ACLR 13 (4 males, 9 females)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>19.13 ± 2.18</td>
<td>22.23 ± 2.13</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.77 ± 0.11</td>
<td>1.67 ± 0.07</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>76.03 ± 11.87</td>
<td>65.66 ± 11.33</td>
<td>0.024</td>
<td></td>
</tr>
<tr>
<td>Time from surgery (y)</td>
<td>0.80 ± 0.32</td>
<td>5.70 ± 2.06</td>
<td>0.0001</td>
<td></td>
</tr>
<tr>
<td>Graft type</td>
<td>14 PT, 2 HS</td>
<td>9 PT, 4 HS</td>
<td>0.242</td>
<td></td>
</tr>
<tr>
<td>Spinal-reflexive excitability (H:M)</td>
<td>0.204 ± 0.205</td>
<td>0.283 ± 0.175</td>
<td>0.283</td>
<td></td>
</tr>
<tr>
<td>Active motor threshold (AMT)</td>
<td>41.17 ± 11.95</td>
<td>48.31 ± 10.91</td>
<td>0.132</td>
<td></td>
</tr>
<tr>
<td>Motor evoked potential (MEP:M)</td>
<td>0.072 ± 0.075</td>
<td>0.029 ± 0.035</td>
<td>0.073</td>
<td></td>
</tr>
<tr>
<td>Average MVIC (nm/kg)</td>
<td>2.13 ± 0.98</td>
<td>2.90 ± 0.54</td>
<td>0.020</td>
<td></td>
</tr>
<tr>
<td>Average CAR</td>
<td>83.57 ± 12.96</td>
<td>91.83 ± 6.99</td>
<td>0.054</td>
<td></td>
</tr>
<tr>
<td>ACL-HI</td>
<td>26.19 ± 4.74</td>
<td>24.60 ± 2.84</td>
<td>0.350</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: ACL-HI, anterior cruciate ligament helplessness index; AMT, active motor threshold; CAR, central activation ratio; H:M, Hoffmann reflex normalized to muscle response; HS, hamstring graft. MEP, motor evoked potential; MVIC, maximum voluntary isometric contraction; PT, bone patellar tendon bone autograft.

Early ACLR

In the early recovery group, the PCA analysis revealed 5 components that had eigenvalues greater than one and which explained 31.97%, 20.78%, 14.77%, 8.4% and 7.3% of the total variance of the entire ACL-HI scale, respectively. In totality, the five-component solution explained 83.27% of the total variance. There were strong loadings of “coping attributes” items on Component 1, “cognitive readiness” items on Component 2, “pain management” items on Component 3, “accountability” items on Component 4 and self-awareness/management attribute items on Component 5. Component loadings and the rotated component matrix are presented in Table 2. Component 2 (cognitive readiness) was moderately associated averaged normalized MVIC of the ACL limb ($r^2=0.513$, $p=0.004$) where greater cognitive readiness was related to greater quadriceps isometric strength. Component 5 (self-awareness/management) was
moderately and negatively associated with AMT of the ACL limb \( (r^2=0.238, p=0.05) \), (Figure 1 & Figure 2) indicating that greater self-awareness and self-management skills are related to lower active motor thresholds.

**Table 6.2. Component loadings and the rotated component matrix for the early recovery ACLR group on the 15 item ACL-HI**

<table>
<thead>
<tr>
<th>Item</th>
<th>Component 1 (Coping ability)</th>
<th>Component 2 (Cognitive readiness)</th>
<th>Component 3 (Pain management)</th>
<th>Component 4 (Accountability)</th>
<th>Component 5 (Self-awareness/management)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q6</td>
<td>0.837</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q8</td>
<td>0.823</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q13</td>
<td>0.816</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q5</td>
<td>0.778</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q1</td>
<td>0.711</td>
<td>-0.433</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q2</td>
<td>0.671</td>
<td>0.442</td>
<td>0.470</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q9</td>
<td>0.669</td>
<td></td>
<td></td>
<td>0.594</td>
<td></td>
</tr>
<tr>
<td>Q15</td>
<td>0.795</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q3</td>
<td>0.791</td>
<td></td>
<td></td>
<td>0.507</td>
<td></td>
</tr>
<tr>
<td>Q7</td>
<td>-0.790</td>
<td></td>
<td></td>
<td></td>
<td>0.470</td>
</tr>
<tr>
<td>Q10</td>
<td>-0.729</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q4</td>
<td>0.873</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q14</td>
<td>0.832</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q2</td>
<td>0.893</td>
<td></td>
<td></td>
<td></td>
<td>-0.821</td>
</tr>
<tr>
<td>Q11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Component values between 0.7 and 1 are considered strong while values between 0.4 and 0.7 are characterized as moderate. Values under 0.4 were not included within these analyses as they represent weak to meaningless factor loadings.
Late ACLR

In the late recovery group, the PCA analysis revealed 4 components that had eigenvalues greater than one and which explained 37.34%, 16.97%, 16.24% and 12.72% of the total variance, respectively. In totality, the four-component solution explained 83.27% of the total variance. There were strong loadings of “mindful of impairment” items on Component 1, intrinsic helplessness items on Component 2, “functional awareness” items on Component 3 and “external support” items on Component 4. Component loadings and the rotated component matrix are presented in Table 3. Component 2 (intrinsic helplessness) was associated with MEP:M at 120% of AMT in ACL limb ($r^2=0.653$ p=0.005) (Figure 3). Specifically, in late recovery ACLR patients, greater intrinsic helplessness was associated with reduced motor evoked potentials.
Table 6.3. Component loadings and the rotated component matrix for the Late ACLR group on the 15 item ACL-HI

<table>
<thead>
<tr>
<th>Item</th>
<th>Component 1 Impairment mindfulness</th>
<th>Component 2 Intrinsic helplessness</th>
<th>Component 3 Functional awareness</th>
<th>Component 4 External support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q12</td>
<td>0.927</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q13</td>
<td>0.895</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q1</td>
<td>0.759</td>
<td></td>
<td>0.419</td>
<td></td>
</tr>
<tr>
<td>Q14</td>
<td>0.669</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q3</td>
<td></td>
<td>0.864</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q11</td>
<td>-0.496</td>
<td>-0.790</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q8</td>
<td></td>
<td>0.771</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q15</td>
<td>-0.677</td>
<td>-0.449</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q5</td>
<td></td>
<td>0.867</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q4</td>
<td></td>
<td>0.824</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q2</td>
<td>-0.471</td>
<td>0.764</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q6</td>
<td>0.442</td>
<td></td>
<td>0.693</td>
<td></td>
</tr>
<tr>
<td>Q7</td>
<td></td>
<td></td>
<td>0.901</td>
<td></td>
</tr>
<tr>
<td>Q9</td>
<td></td>
<td></td>
<td>0.822</td>
<td></td>
</tr>
<tr>
<td>Q10</td>
<td></td>
<td>-0.523</td>
<td>0.680</td>
<td></td>
</tr>
</tbody>
</table>

Note: Component values between 0.7 and 1 are considered strong while values between 0.4 and 0.7 are characterized as moderate. Values under 0.4 were not included within these analyses as they represent weak to meaningless factor loadings.
6.5 DISCUSSION

In order to better understand the complex and multifactorial nature of neural and psychological environments after ACLR, the purpose of this study was to evaluate whether underlying constructs of LH differed between early and late ACLR patients and how these LH constructs interacted with neural activity and quadriceps function. A descriptive figure representing our global findings are depicted in Figure 4. We observed that in the early ACLR group, greater cognitive readiness and self-awareness/management attributes were related to higher isometric quadriceps strength and lower AMTs (i.e. less stimulation needed to cause depolarization of neurons in the primary motor cortex), respectively. In the late ACLR group, more intrinsic helplessness was associated with reduced MEPs (i.e. less information from the brain received at the quadriceps muscle). Understanding how neurological alterations and functional deficits
are related to LH after ACLR can provide clinicians with a greater understanding of the potential role that psychological function may play in a patient’s recovery.

![Diagram of Recovery Timeline]

**Figure. 6.4** Neuroplasticity and helplessness constructs differ between early and late recovery ACLR patients.

Our findings support that patients in the early ACLR group exhibited reductions in quadriceps strength compared with the late ACLR group (Table 1) and these strength deficits were associated with greater LH attributes (Figure 2). Further, while AMT was not statistically different between early and late ACLR groups, reductions in corticospinal excitability in the early group were also strongly associated with greater helplessness attributes (Figure 3). We believe this timeline of events follows the expected trajectory of well-established neural changes. For instance, there are various phases of recovery where neural activity is altered. Initial, acute changes in spinal-reflexive excitability have been proposed to promote late phase neuroplasticity of the brain. Specifically in late recovery ACLR patients (Heroux and Tremblay 2006, Pietrosimone, Lepley et al. 2013, Lepley, Gribble et al. 2015, Bodkin, Norte et al. 2019,
Lepley, Grooms et al. 2019) there is evidence of reductions in corticospinal excitability, where both higher stimulus thresholds and reduced motor outputs are observed.(Lepley, Gribble et al. 2015) Ultimately, the combination of these early and late neural deficits directly influences quadriceps function, initially during the early phases of recovery but have also been shown to drive persistent functional deficits.

Previous work has supported that early changes in the responsiveness of spinal reflexive pathways may prime the central nervous system to reorganize and initiate neuroplasticity within the brain.(Needle, Lepley et al. 2017) These neural changes, specifically to the motor cortex, have been proposed to occur as early as 3–6 months after ACLR. Clinically we observe these alterations in corticospinal excitability as higher cortical thresholds (greater AMT) and reductions in motor output (lower MEP). The findings from our investigation descriptively agree (Table 1) with previous research highlighting reduced corticospinal excitability in late recovery ACLR patients. Physiologically this is logical as corticospinal alterations have been suggested to continue to progress the further patients are removed from surgery.(Lepley, Gribble et al. 2015, Pietrosimone, Lepley et al. 2015, Needle, Lepley et al. 2017, Bodkin, Norte et al. 2019, Lepley, Grooms et al. 2019)

As it is clear that neural activity changes along a continuum, it is likely that neurocognitive function, specifically LH, would most likely arise during the time when brain neuroplasticity is occurring.(Burland, Lepley et al. 2019) Initial motor threshold alterations that lead to functional deficits (i.e. quadriceps weakness, altered motor patterns) can foster an environment of uncontrollability, initiating the development of LH. On the other hand, protracted changes in corticospinal excitability (higher AMTs, lower
MEPs) may eventually lead to distinct whole-brain neuronal changes that can directly influence brain regions devoted to processing of emotional responses associated with LH. While the overall summed LH score on the ACL-HI was not different between the early and late groups, differing aspects of neural activity that were associated LH attributes were observed between early and late ACLR patients.

A novel aspect of this study was the ability to evaluate the interactions between neural alterations and attributes of LH, an area where research is limited. (Pietrosimone, Lepley et al. 2013) Recent theoretical work has proposed that the cortical neuroplasticity that occurs as a result of ACL injury may promote an environment ripe for the development of neurocognitive deficits, specifically LH. (Burland, Lepley et al. 2019) The present study highlights that reductions in corticospinal excitability are associated greater helplessness attributes in both the early and late ACLR groups. Higher motor thresholds (indicating depressed corticospinal excitability) in the early ACLR group were associated with reduced self-awareness/management. As the self-awareness/management component (Table 2, Figure 2) is an attribute of helplessness, it is interesting to note that these findings support previous preliminary work (Burland, Lepley et al. 2019) that greater helplessness (i.e. in this case reduced ability to be self-aware or manage a situation after ACL injury) may be associated with decreased ability to excite descending cortical neurons and thus in impairment in voluntary motor control. Conversely, in the late ACLR group, only reductions in motor output were associated with greater intrinsic helplessness attributes. An individual with higher levels of perceived intrinsic or personal helplessness believes that non-contingency, or the disconnect between a motor response and an outcome, can be attributed directly to
uncontrollable internal factors. (Quinless and Nelson 1988) Interestingly, the results from the early recovery group suggest that managing self-awareness and self-management skills early on in recovery may help promote improved outcomes after ACLR, as it was associated with greater corticospinal excitability. Conversely, based on the findings from the late ACLR group it seems as though intervention strategies aimed at integrating incremental and obtainable learning goals throughout recovery, especially during the later stages may help to reduce and individual’s tendency towards feeling intrinsically helpless. Based on the balance of data evaluating corticospinal excitability after ACLR and the findings from the current study, it appears that increases in motor threshold may occur prior to and subsequently drive reductions in motor output.

Taken together, this work provides evidence to support the notion that there is an interaction between neural alterations and neurocognitive deficits, specifically helplessness attributes, after ACLR. Our preliminary results have clinical implications for instance, while therapeutic interventions to mitigate neurological alterations are still emerging, there are numerous clinically feasible and affordable psychological strategies that can be implemented to deter helplessness attributional styles. Improving cognitive readiness and self-awareness/management attributes and decreasing intrinsic helplessness through targeted interventions aimed at improving an individual’s perception that their “failure” or inability can be overcome by their effort can be useful. (Stipek and Kowalski 1989) Specifically, the emphasis of formulating goals that promote learning and increases in ability over time versus simply performance style evaluations may help promote successful mastery-oriented response to common obstacles faced during recovery, thus decreasing helplessness. (Elliott and Dweck 1988,
Additionally, guided imagery, relaxation techniques and mindfulness techniques may help to further reduce psychological dysfunction and helplessness in patients after ACLR. (Cupal and Brewer 2001, Mendonza, Patel et al. 2007)

Limitations

There were several limitations of this study. Most importantly due to the nature of the study design, the findings of this study are preliminary and do not establish a causal link between neural alterations and LH. Also, this is a small cohort (n=29) of ACLR individuals that were categorized into early and late phase recovery and limit the generalizability of the findings. Future research with a larger sample size should be conducted to expand on the relationship between neural alterations, quadriceps function and LH after ACLR. Secondly, these outcome measures were only obtained at a single timepoint after ACLR and we cannot comment on these patients’ neural activity, quadriceps function and psychological wellness prior to undergoing surgery. Individuals who have greater alterations in neural activity or quadriceps dysfunction prior to ACLR may have less optimal outcomes compared with those who present more favorably. Further, it is unclear whether psychological dysfunction is a predisposing factor to ACL injury. (Swanik, Covassin et al. 2007) Individuals with greater psychological dysfunction pre-injury or pre-surgery may be more predisposed to depression and helpless like symptoms after recovery. (Wu, Liu et al. 2016) Future studies should not only include evaluation of these measures prior to ACLR but should also serially evaluate both changes in neural activity and LH attributes throughout recovery. Because helplessness presents similarly to many fear avoidance behaviors, future research should include
evaluation of fear or anxiety related factors after ACLR to provide a comprehensive assessment of psychological function.

6.6 CONCLUSION

Learned helplessness is made up of several attributional constructs which are altered at different phases of recovery after ACLR. Additionally, these underlying LH constructs interact differently with neural activity and quadriceps function across time. In the early ACLR group, greater cognitive readiness and self-awareness/management attributes were related to higher isometric quadriceps strength and lower AMT. In the late ACLR group, more intrinsic helplessness was associated with reduced MEPs. These preliminary findings provide us clinically relevant areas to focus on after ACLR. Specifically, targeting cognitive readiness when completing physical tasks, being more self-aware and able to self-manage may promote better function early on in recovery. Additionally, establishing learning-oriented goals versus mastery type goals throughout rehabilitation and recovery may help to reduce greater intrinsic helplessness in patients further removed from surgery.
CHAPTER 7. Summary and Future Directions

7.1 Summary & Clinical Bottom Line

The overall purpose of this dissertation was to comprehensively investigate the consequences that arise after ACLR. We sought to independently explore relationships between neural activity, quadriceps strength, biomechanics, self-reported/psychological function and the presence of learned helplessness after ACLR for the purpose of identifying modifiable factors that have direct implications for clinical care after ACLR. The central constructs discussed in this dissertation point to the multifaceted nature of ACL injury and reconstruction outcomes and highlight that the blending of physical and psychological recovery is a relatively novel aspect of clinical care.

In Chapter 3 we evaluated the extent of disagreement between hop distance symmetry and biomechanical symmetry within individual hop trials in patients who on average achieve symmetry on the clinical TrH task after ACLR. The findings of the present study suggest that clinical and biomechanical assessments are capturing different elements of neuromuscular control and physical function. When evaluating between trial agreement for distance hopped symmetry and knee biomechanics, there was increased variability and no agreement between passing clinical and biomechanical variables. Based on the findings of this study, distance hopped during the clinical TrH task is not a substantial indication of how someone would biomechanically perform the same task. Future research should consider re-evaluating the physical performance tasks used to progress individuals back to functional activities and limit emphasis of “average” performance and focus on incorporating movement strategies that are representative of both physical and biomechanical function. Clinical bottom line:
Health care clinicians should incorporate individual trial-by-trial analyses when evaluating physical performance metrics, specifically hop for distance tasks, after ACLR and upon resuming functional activities. Utilizing this strategy can allow clinicians to objectively recognize variability in performance and potentially intervene through additional rehabilitative therapy to improve limb symmetry and movement quality.

In Chapter 4 to provide a comprehensive view of patient function we explored what underlying factors drove individuals to report poorly on common PROs used after ACLR. Participants who exhibited greater internal motivation, confidence and a support network during recovery had improved PROs. Participants with avoidance tendencies, fear, lack of clear expectations and support scored worse on PROs. Further, PROs including the TSK, ACL-RSI and KOOS-QOL were able to capture both psychological and physical constructs influencing perceived wellness. Most importantly these data enforce that recognizing and addressing common facilitators (i.e. greater internal locus of control, confidence, social support, clear expectations) and barriers (i.e. avoidance behaviors/fear, insurance limitations) during recovery can help improve an individual's ability to maintain overall physical health and quality of life. Clinical bottom line: Patients after ACLR, whether they report well or poorly on common PROs, all experience similar facilitators and barriers during rehabilitation. Some patients, however, experience psychological and physical barriers to a lesser extent and this promotes their ability to remain positive and have an overall better outlook during recovery. Identifying both barriers and facilitators using PROs such as the TSK, ACL-RSI and KOOS-QOL can help clinicians identify individuals who may benefit from
psychological counseling or psychological interventions such as guided imagery, goal setting and mindfulness exercises.

The consequences of sustaining an ACL injury are vast, including both physiological and psychological responses. In Chapter 5, we proposed a theoretical hypothesis that depicts the interaction between neural alterations and psychological deficits, where there is a potential for nervous system alterations to promote LH after ACLR. To provide comprehensive patient care after ACLR, we need to consider psychological health during ACL rehabilitation and recognize LH as a potential barrier to successful recovery. Future studies should evaluate longitudinal changes between neural and psychological factors which can help us further develop targeted interventions capable of mitigating this modifiable factor. Clinical bottom line: The preliminary link between neural alterations and psychological dysfunction necessitates the integration of clinical therapies that target the nervous system (i.e eccentric cross-exercise, disinhibitory modalities [TENS, NMES], tDCS) that can help to reverse the neural alterations commonly observed after ACLR. In conjunction, integrating psychosocial behavior techniques aimed at improving motor control through learning type exercises, goal setting strategies, and other cognitive behavioral techniques (imagery, mindfulness, relaxation breathing) can help to improve psychological function after ACLR.

In Chapter 6 we explored the relationship proposed in our theoretical hypothesis that individuals after ACLR who have greater neural alterations would exhibit greater LH attributes. Specifically, we did this by evaluating patients who were in the early phases of recovery (< 2 years), compared to later stage ACLR patients (> 2 years) as neural
changes, specifically brain mediated corticospinal excitability, has been shown to degrade in the years after ACLR. We observed that early after ACLR, greater cognitive readiness and self-awareness/management attributes were related to higher isometric quadriceps strength and lower AMTs (i.e. less stimulation needed to cause depolarization of neurons in the primary motor cortex), respectively. During the later phases of recovery however, more intrinsic helplessness was associated with reduced MEPs (i.e. less information from the brain received at the quadriceps muscle). While these results are preliminary and more longitudinal research needs to be conducted to examine how these relationships may change throughout the recovery process, it may be helpful to consider the incorporation of feasible strategies aimed at mitigating psychological distress into rehabilitation programs. **Clinical bottom line:** As neural alterations are well-established and extensive after ACLR, using therapies that directly target the nervous system (eccentric cross-exercise, disinhibitory modalities, tDCS) along with incorporation of strategies to improve cognitive readiness when completing physical tasks, encouraging patients to be more self-aware and to self-manage may promote better function early on in recovery. Learning-oriented (external focus, implicit, differential, contextual and self-control learning) versus mastery type goals throughout rehabilitation and recovery may also help patients reduce greater intrinsic helplessness and feelings of uncontrollability. Additionally, focusing on tasks that are within the patients control and removing the emphasis from things that are not within the patients control (due to uncontrollability) can also help to improve psychological function and reduce helplessness. Together, these findings can help direct future studies aimed at
developing more targeted interventions that can optimize psychological function by targeting the nervous system.

7.2 Future Directions

The purpose of this dissertation was to comprehensively investigate the relationships between common post-operative outcomes for the purpose of identifying modifiable factors that hinder rehabilitation success. While the studies in this dissertation provide clinicians with important information regarding the relationships between biomechanics, physical function, neural activity, self-reported/psychological function and LH, there are several areas of limitation where future research can be conducted. Firstly, these studies were all conducted at a single timepoint after ACLR. To further expand on the interrelationships between these constructs, longitudinal work spanning the recovery process (pre-surgery to post-ACLR) is critical. To this end, we have on-going, preliminary, longitudinal work that evaluates neural alterations, physical function and psychological function at pre-surgery, 3-months post-operatively and at the time of clearance after ACLR. The results of this work will help to provide a critical step forward in establishing the initial groundwork for future clinical trials aimed at producing an evidence-based paradigm shift in traditional ACLR rehabilitation where we will be more equipped to systematically address the cause of negative post-surgical outcomes and reduce disability after ACLR. This work is also conceptually novel as for the first time we will investigate the potential of LH in perpetuating existent neural impairments, asymmetries in knee biomechanics, and deficits in strength and self-reported function a three distinct time points after ACL injury and ACLR.
A second limitation of this study was the inability to directly and objectively measure psychological dysfunction or learned helplessness in our patients. As the importance of addressing psychological dysfunction along with physical function after traumatic joint injury continues to grow, directly observing neuropsychological alterations such as LH is imperative to developing appropriate treatment interventions after traumatic joint injury. Future studies that objectively quantify learned helplessness through the use of neural imaging (e.g. diffusion tensor imaging, functional magnetic resonance imaging) can help us to further identify viable treatment interventions. Previous studies conducted on individuals in chronic pain populations have demonstrated increases in cortical thickness in the supplementary motor area and midcingulate cortex, regions implicated in cognitive aspects of motor behavior. Further work performed by Lepley et al (Lepley, Grooms et al. 2019) has identified that patient perceived function (measured using the KOOS pain and symptoms subscale) was significantly associated with increased frontal lobe brain activity. Together, this points to the need for future work that can directly examine brain structures likely to be affected by the presence of psychological dysfunction and learned helplessness in individuals after ACL reconstruction.
APPENDICES
APPENDIX A
Semi-structured, qualitative interview guides
Pre-surgery questionnaire

Demographic Information:
Age:
Year in School:
Gender:
Primary Sport/ level of play:
Dominant Extremity:
Injured Extremity:
- What year in school are you?
- When did the injury occur?
- In what sport did the injury occur?
Surgery date:
1. Walk me through your injury.
   **Probe**: Describe what happened in as much detail as you’re willing to share.
   **Probe**: What led to your anterior cruciate ligament (ACLR) surgery?

2. Describe your initial emotions regarding your injury.

3. What are your expectations regarding your outcomes following ACLR?

4. Describe your confidence in your ability to pick up where you left off/return to the level of play you once were at following ACLR?
   **Probe**: Please explain.

5. Is there anything that worries you about surgery?

6. What personal strategies do you think you will utilize to overcome any barriers following surgery?

7. Is there anything else you would like to share with us or add relative to this topic?
3-month post-surgery questionnaire

Demographic Information:
Age:
Year in School:
Gender:
Primary Sport/ level of play:
Dominant Extremity:
Injured Extremity:
  - What year in school were you?
  - When did the injury occur?
  - In what sport did the injury occur?

Surgery Date:

1. Describe your initial emotions to your injury?
   **Probe:** How did your emotions change over the course of your initial recovery and rehabilitation?

2. Describe your rehabilitation experience thus far?
   **Probe:** (What stands out most to you about the process?)

3. Describe your feelings during rehabilitation thus far?
   **Probe:** Describe any difficulties you’ve experienced in rehabilitation.

4. Describe any expectations regarding your rehabilitation and recovery following ACLR.

5. Have your expectations changed at all since your surgery?
   **Probe:** If they changed, what impacted the change?
   **Probe:** If they didn’t change, how did you know what to expect?

6. Did you face any obstacles or barriers thus far during your recovery?
   **Probe:** Describe how you overcame these barriers.

7. What kind of assistance or additional support do you think athletes who undergo ACLR need throughout the rehabilitation process?
   **Probe:** Describe any support you received.

8. What can be done to help other athletes as they prepare to undergo ACL surgery?

9. Do you believe that your feelings confidence in your knee match knee’s physical function?

10. Is there anything else you would like to share with us or add relative to this topic?
Return to Play (> 6-month) Post-Surgery Questionnaire

Demographic Information:
Age:
Year in School:
Gender:
Primary Sport/ level of play:
Dominant Extremity:
Injured Extremity:
  - What year in school are you?
  - When did the injury occur?
  - In what sport did the injury occur?

Surgery date:

1. Walk me through your injury.
   **Probe:** Describe what happened in as much detail as you're willing to share.
   **Probe:** What led to your anterior cruciate ligament (ACLR) surgery?

2. Describe your initial emotions to your injury.
   **Probe:** Describe how these emotions changed over time.

3. Describe your initial emotions to your rehabilitation experience.
   **Probe:** Describe how these emotions changed over time.

4. Describe what you believe was the most difficult part of your rehabilitation.
   **Probe:** Did this change your adherence to rehab?
   **Probe:** What allowed you to follow your rehabilitation program?

5. What obstacles or challenges did you face during your rehabilitation/return to sport?
   **Probe:** Describe whether these impacted your ability to remain compliant and follow your guidelines for returning to your sport?

6. Describe whether you were able to overcome these barriers.
   **Probe:** Describe any factors that helped you overcome these barriers.

7. Did you face any obstacles when you returned to your sport?
   **Probe:** If so, please describe them.
   **Probe:** If not, why do you think you were able to return to your sport without issue?

8. What kind of assistance or additional support do you think athletes who undergo ACLR need throughout the rehabilitation process?
   **Probe:** Describe any support you received.
9. What can be done to help other athletes as they prepare to undergo ACLR or prepare to return to sport?

10. Overall do you believe your ACLR was successful in returning your physical function?
   **Probe:** Describe your response.

11. Do you believe that your return to sport status is successful?
    **Probe:** Please expand on your response.

12. Do you believe that your confidence in your knee match your knee’s physical function?

13. Is there anything else you would like to share with us or add relative to this topic?
APPENDIX B

Quote 1: “Definitely the emotional [aspects] because you don’t want to like you know, go too hard because you’re always thinking like what if I tear it again… cause it’s not you know as strong as the original one.”

Quote 2: “I think more mentally than physically, like I’m still cautious. The fear of re-tearing my ACL or do something to screw up my surgery. I haven’t even gotten on a mountain bike since before my surgery because is that one ride really worth being on crutches for however many weeks.”

Quote 3: “I was so motivated to improve once I was cleared to do anything I needed to do during rehabilitation… [I used] motivational factors of my own, I was very intrinsically motivated, I just wanted to be as healthy as I could be as fast as I could be.”

Quote 4: “I wanted to keep playing sports for a while…so there is not a reason to sulk and I knew if I did a good job with physical therapy [that] I would be better off post-rehab.”

Quote 5: “I was pretty self-motivated… [after the injury] it just really motivated me to not ever have someone have to care for me like that again.”

Quote 6: “I would do all the exercises when I was there [physical therapy]”

Quote 7: “I feel like I can do any sport I want to do, but I always wear the brace.”

Quote 8: “My whole goal was to play sports again and I feel like I can do any sport I want to do.”

Quote 9: “My parents were really supportive and my friends and teammates obviously they were always asking me if I was okay and making sure that I was good and telling me that they missed me and stuff.”

Quote 10: “I think that [athletes need additional support] from their athletic trainer or physical therapist, it’s really important to understand that those healthcare providers are there for them and have their best interest in mind.”

Quote 11: “I still have a lot of locking when I sit for too long…and I have pain when I sit in the same position for a long time.”

Quote 12: “My functioning is not where it should be.”

Quote 13 “I kind of dreaded going because I knew they were going to push it a little farther every day, and I felt that my knee was going to snap, and I hated it.”

Quote 14: “I was frustrated with that [only 4 months of therapy] because we couldn’t fully get the whole [physical function back] …we did jumping stuff, cutting stuff as much as we could, but I never felt like I got my full strength back…everything else I did on my own.”
APPENDIX C
Learned Helplessness Scale

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No matter how much energy I put into a task, I feel I have no control over the outcome</td>
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<td>2. I feel that my own inability to solve problems is the cause of my failures</td>
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<td>3. I cannot find solutions to difficult problems</td>
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<td>4. I don’t place myself in situations where I cannot.</td>
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<td>5. If I complete a task successfully, it is probably because I became lucky</td>
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<td>6. I do not have the ability to solve most of life’s problems</td>
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<td>7. When I do not succeed at a task I do not attempt any similar tasks because I feel that I will fail them also</td>
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<td>8. When something doesn’t turn out the way I planned, I know it is because I didn’t have the ability to start with</td>
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<td>9. Other people have more control over their success and/or failure than I do.</td>
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<tr>
<td>10. I do not try a new task if I have failed similar tasks in the past</td>
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<tr>
<td>11. When I perform poorly it is because I don’t have the ability to perform better.</td>
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<tr>
<td>12. I do not accept a task that I do not think I will succeed in.</td>
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<tr>
<td>13. I feel that I have little control over the outcomes of my work</td>
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<td>14. I am unsuccessful at most tasks I try</td>
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<td>15. I feel that anyone else could do better than me in most tasks</td>
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<tr>
<td>16. I am unable to reach my goals in life</td>
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<tr>
<td>17. When I don’t succeed at a task, I find myself blaming my own stupidity for my failure</td>
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<tr>
<td>18. No matter how hard I try, things never seem to work out the way I want them to</td>
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<tr>
<td>19. I feel that my success reflects chance, not my ability</td>
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<td>20. My behavior does not seem to influence the success of a work group</td>
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</table>

LH Scale Instructions: Place an X in the response box which most closely describes how you feel about each item.
APPENDIX D
Anterior Cruciate Ligament Helplessness Index

ACL Injury Helplessness Index: In the following instrument, there are statements that you are asked to read carefully. After reading each item, respond as to how closely you agree or disagree with how each item describes you and your feelings about yourself.

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. My knee injury is controlling my life</td>
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<td>2. Managing my knee injury is largely my own responsibility</td>
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<td>3. I can reduce my pain by staying calm and relaxed</td>
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<td>4. Too often, my pain just seems to hit me out of the blue.</td>
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<td>5. If I do all the right things, I can successfully manage my knee injury.</td>
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<td>6. I can do a lot of things myself to cope with my knee injury.</td>
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<td>7. When it comes to managing my knee injury, I feel I can only do what my doctor tells me to do.</td>
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<td>8. When I manage my personal life well, my knee injury does not flare up as much.</td>
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<td>9. I have considerable ability to control my pain.</td>
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<td>10. I would feel helpless if I couldn't rely on other people for help with my knee injury.</td>
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<td>11. Usually I can tell when my knee injury will flare up.</td>
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<tr>
<td>12. No matter what I do, or how hard I try, I just can't seem to get relief from my pain.</td>
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<tr>
<td>13. I am coping effectively with my knee injury.</td>
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<tr>
<td>14. It seems as though fate and other factors beyond my control affect my knee injury.</td>
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<tr>
<td>15. I want to learn as much as I can about knee injury.</td>
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</tbody>
</table>

Place an X in the response box which most closely describes how you feel about each item.
APPENDIX E

Institutional Review Board Form 1

IRB-1 Study Protocol

Protocol Version # and/or Date:  Version 5, September 14, 2018; Protocol # H16-120

Study Protocol Title: Examining Barriers, Facilitators and Physical Function in Individuals Following Anterior Cruciate Ligament Reconstruction.

Research Plan

Purpose/Introduction

State the reason for the study, the research hypothesis, and the goals of the proposed study as related to the research question(s). Provide a clear and succinct summary description of the background information that led to the plan for this project. Provide references as appropriate and, when applicable, previous work in animal and/or human studies. Provide previous UConn protocol number, if applicable.

Anterior cruciate ligament (ACL) injury is one of the most common, debilitating knee injuries sustained in athletic populations and often leads to functional impairments, subsequent re-injury and long-term joint morbidity.1-4 Surgical intervention is often recommended for athletes who have sustained an ACL injury that desire to return to high levels of physical activity, specifically those involving cutting and pivoting.2,5-8 Although an ACL reconstruction (ACLR) is considered to be the most reliable method for regaining function and returning athletes to pre-injury activity levels, recent literature has demonstrated that the number of athletes returning to sports participation is lower than previously thought.9-14 These studies have reported that only 65% returned to their preinjury level of sport and 55% returned to competitive sport, despite achieving successful surgical outcomes.13,15-18 In other words, after ACLR 1 in 3 individuals did not return to their previous level of sports participation, and 1 in 2 did not return to competitive sport after surgery. Aside from functional impairment, numerous psychosocial factors, such as fear of reinjury, kinesiophobia, change in level of play and loss of motivation17,19, have also been identified and potentially contribute to the failure of athletes returning to sport. Based on the suboptimal outcomes associated with the rate of athlete that return to play after ACLR and the concurrent deficits in psychosocial factors that have been found to influence function, it is our contention that an individual's decision to return-to-sport is likely multifactorial, dependent on physical, environmental and psychological influences.

Few studies have concurrently examined how athletes make return-to-sport decisions and how deficits in knee function affect patient satisfaction after ACLR. Past research has thoroughly examined both clinical knee outcomes as well as objective knee function as determinants for progression and return to sport.20-25 The growing body of literature on recovery following ACLR encourages clinicians to utilize clinical cut-offs to objectively measure knee function for return to sport.26 Specific functional measures such as isokinetic & isometric strength testing, as measured on a dynamometer, are frequently used to help determine limb
symmetry of muscle strength and functional performance.21 These strength tests are frequently used at specific time-points post-operatively, designated by the treating physician or therapist, as a method of assessing progress throughout the rehabilitation process. Other methods for gauging readiness to return includes a series of single legged hop tests and drop jump landings, which can additionally be assessed with electromyography to assess muscle activation during the tasks. Clearance criteria for return to sport to date normally includes lower limb symmetry measures that are >90% of the contralateral side.9,27

In addition to the physical trauma, individuals who suffer from traumatic joint injuries often experience psychological responses in addition to functional impairment.17,19,28,29 While significant progress has been made in understanding the physical impairments that are present at RTP after ACLR, the psychological aspects of ACL are less understood. Recent literature suggests that there are numerous psychosocial responses that may occur following ACLR and can act as potential barriers to successful return to sport.17,28,30-33 These factors may range from a general loss of interest in sport, change in level of play (high school to college), and fear of re-injury.17-19,34-37 Other factors such as lifestyle changes, occupational demands, loss of motivation and perceived self-efficacy may contribute to whether or not athletes return-to-sport at any given level.29,38

Numerous studies have examined factors that have the ability to influence successful return to sport.23,32,39,40 However, longitudinal investigations examining both pre-and post-operative functional measures as well as a qualitative exploration of the athlete's perceived barriers encountered and success regarding their recovery experience is limited. It is unknown if barriers faced during recovery (i.e. adherence, motivation, individual expectations, self-efficacy, etc.) influence individual perceived success in regards to both objective knee function and successful return to preinjury sport. Identifying these barriers both pre-surgery and post operatively in conjunction with functional performance measures (i.e. strength, landing and jumping biomechanics and proprioception) may provide clinicians with a better understanding of the role psychological recovery plays in regaining physical function and how this affects both the ultimate outcome upon return to sport and the perceived success of the athlete following ACLR. Additionally, a healthy, pair-matched control group will also be measured to investigate how normalized functional performance measures compare to ACL reconstructed individuals.

**Aim 1:** Using a cross-sectional approach, we will test the hypothesis that barriers identified through qualitative interviews will negatively influence patient self-reported and physical function after ACLR. Additionally, we will test the hypothesis that facilitators identified through the qualitative interviews will positively influence patient self-reported and physical function after ACLR leading to a successful return to preinjury level of sport.

**Aim 2:** Using a cross-sectional approach, we will test the hypothesis that an individual's perception of success after an ACLR does not match their level of physical activity participation and physical function.

**Aim 3:** Using a longitudinal study approach, we will test the hypothesis that individuals that demonstrate higher levels of psychological readiness and higher levels of physical function pre-surgery, will have improved outcomes following ACLR at clearance to return to sport, compared with those who are less physically and psychologically prepared. Additionally, we will explore the relationship between individual's pre-surgery expectations and post-operative expectations to better understand if pre-surgery expectations match actual perception at return to sport.
Design, Procedures, Materials and Methods

Describe the study design, including the sequence and timing of all study procedures. Indicate expected start and completion dates. Include screening procedures, if any. The IRB strongly suggests that investigators incorporate flexibility into the study design to accommodate anticipated events (i.e. explain how missed study appointments can be made up by participants). If the research involves study of existing samples/records, describe how authorization to access samples/records will be obtained. If the study involves use of deception explain the reason why this is necessary. If applicable, describe the use of audiotape and/or videotape and provide justification for use. If this study offers treatment for the participants' condition, complete the Treatment Study Supplemental Form (IRB-1C) and attach it to this application for review. If the study includes measures, survey instruments and questionnaires, identify each and, if available, provide references for the measures. Describe what they intend to measure (relate to purpose/hypothesis) and their psychometric properties (e.g., reliability and validity). Identify any that were specifically created for the study.

We expect to begin the study in July 2016 (pending IRB approval) and complete in 2020. We will begin participant recruitment upon IRB approval. Participants and their legal guardian (if participants are under 18 years old) who volunteer to participate will complete approved assent and consent forms, respectively.

This will be a mixed analysis study.

We will reach out to local and statewide sports medicine clinics as well as through word of mouth on the University's campus. Additionally, we will use web-based platforms and social media outlets to share information regarding study participation to increase recruitment efforts. Individuals who are interested and contact our recruiters will further be contacted with more specific information, detailing their specific participation criteria dependent on their ACL reconstruction status.

Prior to the start of Aim 1, a pilot study will occur. For this pilot study we will use a case-series design and recruit six individuals who have been cleared to return to sport by their treating physician and are at least 6 months' post ACLR. These participants will serve as pilot data for Aim 1 (cross-sectional). For both Aim 1 and Aim 2 portions of this study, at the first baseline testing session, all participants will complete questionnaires including: a laboratory-specific demographic and family history questionnaire, two standardized questionnaires to evaluate current knee function (International Knee Documentation Committee (IKDC) Participant Knee form & Knee Injury and Osteoarthritis Outcome Score (KOOS)), three standardized questionnaires to evaluate participant's feelings about physical activity, the Tampa Scale of Kinesiophobia (TSK), Anterior Cruciate Ligament Return to Sport After Injury scale (ACL-RSI) & Knee Self Efficacy Scale (K-SES), one standardized questionnaire to measure their physical activity participation (Tegner/Lysholm Activity Scale), two questionnaires to evaluate participant's general psychological wellness (Learned Helplessness Scale(s)) and two additional questionnaires to evaluate participant's general quality of life, Short Form 36 (SF-36) and Veterans Rand 12 (VR-12) and one questionnaire to evaluate lateral preference (Lateral Preference Inventory).
**Aim 1:** Aim 1 of the study will be cross-sectional in design to examine which barriers and facilitators influence patient self-reported outcomes and physical measures following ACLR. Within Aim 1, participants will have one test session that will occur post-operatively following clearance to return to sport by their treating physician and will include a battery of physical measures and functional tests (listed below) as well as a qualitative interview and will last approximately 120 minutes.

**Aim 2:** Aim 2 of the study will utilize a cross-sectional approach to determine whether an individual's perception of success after ACLR matches the level of physical activity participation and physical function. Within Aim 2, participants will have one test session that will occur post-operatively following clearance to return to sport by their treating physician and will include a battery of physical measures and functional tests (listed below) as well as a qualitative interview and will last approximately 120 minutes.

**Aim 3:** Aim 3 of the study will utilize a longitudinal study design to investigate 1.) how pre-operative function influences level of physical function attained following ACLR and subsequent physician clearance for return to sport and 2.) whether an individual's pre-surgery expectations differ from perceptions of success following ACLR. Previous research has found that pre-operative quadriceps activation and strength after ACL injury are related to the level of post-operative activation and strength at return to activity 41. Given the relationship between pre-and post-operative quadriceps strength and neural activity, we are interested in investigating how clinical measures of pre-operative quadriceps function and expectations regarding ACLR compare with post-operative measures of function and clearance to return to sport. By closely examining the relationship between pre-and post-operative measures on physical function and psychological readiness to return, we may determine an optimal timing for ACL reconstruction surgery to optimize pre-operative therapy opportunities and promote improved post-operative function. Within Aim 3 there will be three test sessions. The first test session (Session 1) will include participants who are ACL-deficient (ACLD) and have been scheduled ACLR surgery. They will perform a series of functional outcome measurements, deemed appropriate and safe for ACLD individuals, to examine pre-surgery function and muscle activation in addition to completing the above-mentioned self-report questionnaires (detailed below). Additionally, participants will partake in a qualitative interview to examine their expectations regarding recovery and return to sport prior to ACLR. Session 1 will last approximately 120 minutes. The second test session (Session 2) will occur approximately 3 months post-operatively (after ACL reconstruction surgery). This session will include repeating the self-report questionnaires from Session 1 along with the series of functional outcome measurements, deemed appropriate and safe for individuals who are 3 months removed from ACLR. Session 2 outcome measures will examine interim post-surgical function and muscle activation as well as self-reported function. The third test session (Session 3) will occur once the participant has undergone ACLR surgery and has subsequently been cleared to return to sport by their treating physician. This session will include repeating the self-report questionnaires from Session 1 and 2 and performing a battery of functional outcome measurements. Additionally, at this second and final testing time point participants will complete a second qualitative interview at the conclusion of testing to assess what factors influenced their recovery after ACLR and whether their level of physical function and return to sport status matched their perceived satisfaction and success of procedure. All test sessions will take place at the Human Performance Laboratory in the Department of Kinesiology at the University of Connecticut.
To ensure all participants meet inclusion criteria, participants will also be asked to fill out an Inclusion Form (appendix) that contains a comprehensive list of all inclusion and exclusion criteria (separate form for ACL reconstructed individuals and healthy controls) where participants will need to indicate with a single 'yes' or 'no' answer if they have ever been diagnosed or experienced one of the exclusion criteria. The answer to this list of questions will be recorded on the exclusion criteria checklist and utilized to determine if participants meet all inclusion criteria. For female participants that meet inclusion criteria and are willing to undergo electrical stimulation measures, a pregnancy test will also be administered (described in detail below) as the electrical stimulation measures that will be utilized in this study to assess muscle function are contraindicated during pregnancy (approved in IRB H11-035). Female participants that choose to not take the pregnancy test, or have a positive pregnancy test result, will be excluded from participating in electrical stimulation testing only. Participants will still be eligible for all remaining portions of the study. A parent or guardian may be present during both the screening and study procedures.

**Skeletally Immature Participants**

Participants who are minors will complete a modified version of the baseline questionnaire, which will include a question about the participants' biological parents' height if known. Additionally, a modified IKDC knee form, the Pedi-International Knee Documentation Committee Participant Knee form, which is age-dependent will be utilized for participants under the age of 18 to collect information on their current knee function. We will measure the participants' height during the test session and use this value and the parents' values to calculate a value of their % Predicted Adult Height. This tool uses a regression equation to predict adult stature and has been shown to be a valid and reliable measure of skeletal age. Participants who are minors will also complete an additional questionnaire prior to their test session to help us determine their relative skeletal maturity as this may influence their reconstruction. Participants and their legal guardians will be asked to complete the Pubertal Maturational Observational Scale (PMOS) prior to their test session and return this scale in a sealed envelope with only their identification number marked on the scale. This scale has been shown to be a valid assessment tool of pubertal status.

**Pregnancy Test**

For all female participants that are willing to undergo electrical stimulation muscle testing, a pregnancy test (Quidel, QuickVue One-Step hCG Urine test, Fisher Scientific) will be performed onsite in the Human Performance Laboratory prior to any testing according to manufacturer's instructions. Using the following script, it is our plan to ask all female participants willing to undergo electrical stimulation testing to provide a urine sample in a clean urine cup. The research team will then perform the handheld pregnancy test. Please note that prior to arriving for the testing session, during the initial pre-screening meeting (described in detail below), the principal investigator will notify all potential female participants (and their legal guardians if applicable) about the need to screen females for pregnancy, as the electrical stimulation measures that will be utilized in this study to assess muscle function are contraindicated during pregnancy. Additionally, for participants that are minors, in advance of the testing session, the principal investigator will notify the child's pediatrician about the pregnancy test using the primary care physician cover letters (developed with Doug Bradway at the Office of Research Compliance) as it is not appropriate to tell a minor that she is pregnant without informing an adult who can then assist her. If the pediatrician agrees, a signed copy of this form will be
returned to the principal investigator at the testing session. In the event the pediatrician does not provide permission for the pregnancy testing, or a signed copy of the form is not present at the testing session, the female minor participant will not be involved in testing procedures using electrical stimulation.

**Script to be utilized with female participants**

If female participant answers 'yes' to the exclusion criteria form, the participant will be excluded: "Thank you for your time, but unfortunately you do not meet pre-screening criteria. Have a nice day"

If female participant answers 'no' to the exclusion criteria form: "In order to ensure you meet all pre-screening criteria, we need to conduct a pregnancy test to ensure you are not pregnant. We are doing this because some of the electrical stimulation measures involved in this study are potentially harmful to a developing fetus and we want to ensure your safety. The results of this test will be kept in a locked research office and will not be shared with anyone outside of the research team. Are you willing to provide us with a urine sample to conduct this test?"

If 'yes' then the pregnancy test will be conducted.

If 'no' and the participant meets all inclusion criteria and, if applicable, the participant is not pregnant as confirmed by a pregnancy test, the participant will be allowed to participate in the study, including the electrical stimulation testing.

For adult participants, in the event of a positive result, the principal investigator will share the positive test result with the participant in a private setting, and the adult will be excluded from any electrical stimulation procedures. The adult will also be provided with a form with local resources (including UConn Student Health) that can be utilized at their own discretion.

For minor participants, in the event of a positive result, the principal investigator will share the positive test result with the minor in a private setting. It is at the minor's own discretion of whether or not to share this information with their legal guardians. The minor participant will also be handed a form with local resources that can be utilized. Additionally, the principal investigator will notify the child's pediatrician as soon as possible, so that the pediatrician can provide immediate counseling and follow-up for the child.

For minors where child abuse is suspected, in accordance with University policy as a mandated reporter of child abuse, the principal investigator will notify the Department Head and will contact the Department of Connecticut and Families 24-hour hotline for suspected child abuse (1-800-842-2288).

Please note that this plan of action was developed with the assistance of Elizabeth Vitullo at the University of Connecticut’s Office of Audit, Compliance & Ethics and has been discussed with Nancy Wallach and Doug Bradway at the Office of Research Compliance.

**Test Procedures**

All participants will wear a t-shirt, shorts, and athletic shoes to the test session. The participants' height and weight will be measured and the participants' dominant limb will be recorded (limb used to kick a ball for maximal distance) at the beginning of the test session. In light of potential body issues, a research assistant of the same sex as the participant will perform height and weight measurements. Additionally, a research assistant of the same sex as the participant will
assist the participant with any procedure that requires something touching the body. Prior to completing any test, all participants will perform a standardized warm-up consisting of jogging and self-selected stretching exercises. Participants will receive instruction and a model demonstration of each of the testing tasks followed by as many practice trials as the participants indicate they need in order to feel comfortable with the task and perform it correctly. All measurements will be recorded bilaterally in random order during the testing session. Below the testing procedures have been broken down into specific tests that may be utilized by the research team to examine participants with a history of primary ACL reconstruction. The testing procedures will be utilized for both Aim 1 and Aim 2 of the study. In some testing circumstances, such as during Session 1, not all measurements that are detailed below will be utilized. The measures that are taken during the testing session will be dependent on the participant's level of function and laboratory equipment availability (i.e. concurrently in use by another investigation).

ACL reconstructed participants: The following tests have been chosen in order to quantify alterations in movement profiles, functional tasks, strength, balance and neuromuscular control following primary ACL reconstruction (with and without meniscal injury). These tests will allow us to comprehensively examine the level of physical function that is attained following ACL reconstruction. For Aims 1 and 2 of this study, all subsequently listed objective measures are deemed safe and appropriate for ACL reconstructed individuals; participants enrolled in both Aim 1 and Aim 2 will have been released back to full activity prior to completing the testing session. Additionally, the tests performed will depend based on the testing session and specific aim of the study, most specifically for Aim 3 of the study (i.e. pre-operatively (Session 1) versus at 3 months (Session 2) and following return to sport (Session 3) and will be outlined as such below. If a specific test will not be utilized for Session 1 but will be utilized for Session 2 or 3, it will be stated as such next to the specific test.

- Movement tests: (Aims 1 and 2 and Aim 3: Session 3-only)
  - Double-Leg Squat
  - Single-Leg Squat
  - Jump Landing Test
  - Sidestep Cut
  - Dynamic Balance Test
  - Clinical Balance tests: (All Aims and Sessions)
  - Balance Error Scoring System (BESS)
  - Star Excursion Balance Test (SEBT)
  - Muscle Strength tests: (All Aims and Sessions)
  - Knee flexors
  - Knee extensors
  - Hip extensors
  - Hip abductors
  - Hip external rotators
  - Hip internal rotators
  - Range of motion tests: (All Aims and Sessions)
  - Dorsiflexion with knee straight and bent
  - Knee flexion
  - Knee extension (active & passive)
  - Heel height differential (using goniometer)
• Joint Laxity tests: (All Aims and Sessions)
• KT-1000 arthrometer
• Beighton and Horan Joint Mobility Index (BHJMI)
• Functional Performance tests: (Aims 1 and 2 and Aim 3: Session 3- only)
• Single Leg Hop for Distance
• Triple Hope for Distance
• Crossover Hop Test
• Six Meter Timed Hop Test
• Treadmill Walk/Run
• Thigh Girth measurement (All Aims and Sessions)
• Neural excitability Tests: (All Aims and Sessions)
• Quadriiceps Activation Failure (central activation ratio)
• Hoffmann Reflex Test
• Corticospinal excitability testing
• Electromyography (EMG) Tests
• Sonographic Analysis (All Aims and Sessions)
• Semi-Structured Interviews: (All Aims and Sessions)
• Self-reported Questionnaires (All Aims and Sessions)

Motion Capture

Motion during exercise will be captured utilizing one of two methods and synced with surface EMG readings. Both methods are reliable and neither measure increases risk to the participant.

An electromagnetic motion analysis system (Flock of Birds; Ascension Technologies, Inc., Burlington, VT) synchronized with a non-conductive force plate (model 4060-NC; Bertec Corporation, Columbus, OH) will collect three-dimensional lower extremity kinematics and kinetics at sampling frequencies of 144 Hz and 1440 Hz, respectively, during the movement tests. Six electromagnetic sensors will be placed and secured with double-sided tape on the participants’ anteromedial tibialis, lateral thighs, sacrum, and thorax. Bony landmarks will be digitized using a stylus with a fifth sensor attached. A researcher of the same sex as the participant will identify body landmarks and place the electrodes on the participant. Three-dimensional coordinates of the lower extremity and trunk will be estimated using MotionMonitor software (Innovative Sports Technology, Chicago, IL). Euler angles will calculate joint angles of the knee, hip and trunk. All kinematic data will be filtered with a fourth-order low-pass Butterworth filter at 14.5 Hz. Kinematic and kinetic data will be reduced using a customized software program to determine joint angles at initial contact, peak joint angles, and peak joint kinetics. Raw EMG signals will be band-passed filtered 6 to 1000 Hz and subsequently processed using a root-mean-square algorithm with a 50-millisecond moving window. Dynamic EMG collected during the hopping tasks will be normalized to the peak muscle activity that was recorded during dynamic trials. Using this normalization technique, all normalized root-mean-square data were at or below 100% of muscle activity (Approved by IRB Protocol #H11-035).

A 12-camera motion analysis system (Vicon, Oxford Metrics, London, England) that will be synchronized with 2 force-plates (Bertec Corp., Columbus, Ohio) and a wireless EMG system (DTS System, Noraxon Inc, Scottsdale, AZ) will be utilized to quantify three-dimensional biomechanical and muscle activity data, respectively. Lower limb joint rotations will defined
based on three-dimensional coordinates of 32 precisely located retro-reflective markers (right and left limb; anterior and posterior superior iliac spines, iliac crest, greater trochanter, distal thigh, medial and lateral femoral epicondyles, tibial tuberosity, distal shank, lateral shank, medial and lateral malleoli, calcaneus, dorsal navicular, head of first and fifth metatarsal). An initial static trial of each participant aligned with the laboratory coordinate system will be recorded, from which a kinematic model comprising of seven skeletal segments (bilateral foot, shank and thigh segments and the pelvis) and 24 degrees of freedom (6 degrees of freedom for the pelvis relative to the global coordinate system, 3 degrees of freedom for the hip, knee and ankle relative to the local coordinate system) will be created in Visual3D software (C-Motion; Rockville, MD, USA). The three-dimensional marker trajectories recorded during each dynamic landing trial will be subsequently processed within the respective subject's Visual3D model to solve for the generalized coordinates of each frame. Rotations will be calculated utilizing the Cardan rotation sequence (XYZ) and will be expressed relative to each subject's neutral static position. Three-dimensional ground reaction force data will be sampled and synchronized with the kinematic data and both will be filtered using a fourth-order, zero-lag, low-pass Butterworth filter at 12 Hz cut-off frequency. Filtered kinematic and ground reaction force data will then be submitted to a standard inverse dynamics approach within Visual3D. Segmental inertial properties will be defined based on the previous work of Dempster et al. (1959). The intersegmental moments at the knee joint will be expressed as flexion-extension, adduction-abduction, and internal-external rotational moments with respect to the Cardan axes of the local joint coordinate system. Kinetic outputs will be normalized to subject body height and mass and represented as internal moments.

**Movement Tests**

The average across the trials will be calculated for each of the kinematic and kinetic variables associated with the movement tests. Three-dimensional peak knee and hip joint angles will be determined during the stance phase of the jump-landing and sidestep cutting task. The stance phase will be defined as the time period between initial ground contact with the force plate until takeoff for the rebound jump. Initial ground contact is the time when vertical ground reaction force exceeds 10 N as the participant lands on the force-plate from the 30-cm high platform. Takeoff is identified as the time when vertical ground reaction force drops below 10 N. Also, peak vertical ground reaction force and joint moments for hip flexion-extension, hip abduction-adduction, hip internal-external rotation, knee flexion-extension, knee valgus-varus, and knee internal-external rotation will be determined during the stance phase. The peak vertical ground reaction force will be normalized to body weight (N) for each participant (% body weight). For the Double-Leg squat task, three-dimensional peak knee and hip joint angles and moments will be determined during the descent (maximum knee extension to maximum knee flexion) and ascent phases (maximum knee flexion to maximum knee extension) of the task. Peak joint moment data for both tasks will be normalized to the product of body weight (N) and body height (m) (body weight * body height).

All movement and clinical balance tests will be videotaped by two digital cameras, one in the front of the participant and one to the right of the participant in order to capture both frontal and sagittal plane images. The movement tests will be graded at a later date from the videotapes using a standardized clinical movement analysis tool called the Landing Error Scoring System (LESS). The LESS has been shown to be valid and reliable. The LESS is scored based on sixteen readily observable items of human movement when landing and uses a binary system to
determine whether or not the participant demonstrated the landing characteristic or not. A higher LESS score indicates poor technique in landing from a jump; a lower score indicates better technique. Some of the items are assessed at the moment of initial contact with the ground, while others are assessment of motion in the few seconds following initial ground contact. These include: knee flexion angle (how flexed the knee is on initial contact with the ground); knee flexion displacement (how much further the knee flexes following initial ground contact); knee valgus angle (how much the knees point inwards towards one another on initial ground contact); knee valgus displacement (further inwards-pointing knee movement following initial ground contact); stance width (distance between the feet less (or more) than shoulder width on initial ground contact); foot position (toes straight ahead vs. toes in or out); asymmetric foot contact (one foot lands before the other); and ankle plantar-flexion angle (toes land first vs. heels land first), and overall impression of landing "quality." All of these items can be reasonably expected to be associated with an increased force on the ACL.

**Double-Leg Squat (5 repetitions)**

Participants begin with their feet shoulder-width apart, their arms extended straight over their head, and knees and hips in full extension. Participants are instructed to squat down as if they were sitting in a chair and return to the starting position. Specific movements that will be evaluated include: medial knee displacement, foot rotation, approximate degree of knee, hip, and trunk flexion, and lateral trunk movement.

**Single-Leg Squat (5 repetitions per leg)**

This task is identical to the Double-Leg Squat except that it is performed on a single leg and hands on hips.

**Jump-Landing Test (3 repetitions per leg)**

Participants will begin the jump-landing test standing on a box 30 cm high and will jump off the box forward towards a force plate that is placed half the participant's body height away from the box. This distance provides a small challenge to the participant but is not so challenging as to be difficult to perform.

Participants are instructed to immediately recoil and perform a vertical jump for maximum vertical height upon landing (Figure 1) (Test approved by IRB Protocol H11-035).

For the jump landing test an automated scoring system (PhysiHome Technologies LTD, Tel Aviv, Israel) utilizing an Xbox Kinect camera (Microsoft, Redmond, WA) and laptop computer (Dell, Round Rock, TX) will be used. In addition, the jump landing task will be videotaped from the front and side for later review and grading if needed. The jump landing task will be graded using a standardized clinical movement analysis tool called the Landing Error Scoring System (LESS). The LESS has been shown to be valid and reliable. The LESS is scored based on sixteen readily observable items of human movement when landing and uses a binary system to determine whether or not the participant demonstrated the landing characteristic or not. A higher LESS score indicates poor technique in landing from a jump; a lower score indicates better technique. (Approved by IRB Protocol #H11-035).

**Sidestep Cut (5 repetitions per leg)**
Participants will jump forward and down off of a 30-cm high box a distance of half their body height, land with their foot in a target area, and perform a sixty degree cut towards their contralateral side.

**Dynamic Balance (3 repetitions per leg)**

Participants will perform a dynamic balance assessment on both legs. Participants will stand on a 30-cm high box a distance of half of their body height away from the force plate (Bertec Corporation, Columbus, OH). Participants will jump forward from the box off of two feet and land with their foot in the center of the force plate while maintaining their hands on their hips and their other foot off of the ground. Participants will be instructed to balance as quickly as possible without putting their foot down and remain in a single-leg stance for 10 seconds. Trials will be noted and repeated if the participant is unable to maintain this single-limb landing position with their hands on their hips, if a subsequent hop occurs after landing, or if a participant jumps vertically from the box instead of straight down and forward. (Approved by IRB Protocol #H11-035).

**Clinical Balance Tests**

**Balance Error Scoring System (BESS):**

The BESS tests balance ability with participants in two different stances on two surfaces on both legs. Participants stand with their eyes closed and hands on hips during all four tests. The two stances include: Single Leg Stance, and Tandem Stance. The Single Leg Stance requires participants to stand on one foot with their contralateral hip flexed 30 degrees and knee flexed 45 degrees. Participants stand with the heel of one foot touching the toes of the other foot during the Tandem Stance. The two surfaces are a firm, flat surface and a foam pad.

Participants are instructed to assume the standard testing position and remain as still as possible for 20 seconds. Participants are scored based on the number of errors they perform during the 20-second time period. Errors include: Lifting hands off the iliac crest, opening the eyes, stepping, stumbling, or falling, moving the hip into more than 30 degrees of flexion or abduction, lifting the forefoot or heel, or remaining out of the testing position for more than 5 seconds. If a participant cannot maintain the standard position for at least 5 seconds, the score for that trial is a 10 (the maximum score for each trial). Participants will perform one practice trial in each condition followed by 2 test trials in each condition.

**Y-Balance/Modified Star Excursion Balance Test**

Participants will perform a standardized balance assessment called the Star Excursion Balance Test (SEBT) on both legs to evaluate dynamic balance ability. The SEBT involves balancing on one leg while reaching for maximal distance with the other leg in three directions, which are indicated by tape on the ground. Participants start with both feet in the center of the star and must keep their hands on their hips, their stance foot in the same position, and their stance heel on the ground while they perform the test. A research assistant will mark the maximal distance reached for each trial. The three directions include: anterior, posterolateral and posteromedial. Participants will complete four practice trials in each direction followed by three test trials.

**Muscle Strength Tests (2 repetitions of each per leg)**
A hand-held dynamometer be used to measure isometric strength of six different muscle groups as well as the limb weight of each participant's lower limbs. Each limb will be weighed with the participant in a supine (laying down face-up) on the table. Each limb's heel will be rested on the hand-held dynamometer with the knee in extension. The participants will be instructed to relax during the 2-second measurement. For knee flexor and extensor strength, an isokinetic dynamometer (Biodex System 4, Biodex Medical Systems, Shirley NY) will also be utilized to quantify isometric and isokinetic strength of the quadriceps and hamstring muscle groups.

**Knee Flexors**

Hand-held dynamometer protocol: Participants are placed in a prone lying position (face down) with their test leg in 90° of knee flexion. The dynamometer is placed over the posterior aspect of the participants' shank, just proximal to the ankle joint. The participants are instructed to flex their knee with maximal effort.

Isokinetic dynamometer protocol: For isometric strength, the participants will be asked to perform a series of maximal voluntary contractions (MVCs) over a knee range between 10 and 90° of flexion, at 20° decrement (10, 30, 50, 70, and 90° of knee flexion) in a random order. After a practice trial, 3 attempts of 5-second MVCs will be allowed in each joint position with 15-second rest in-between trials. The highest force among 3 attempts will be utilized to represent the peak isometric MVC at that knee position. For isokinetic strength, the participants will be asked to perform a series of MVCs over a knee joint range between 10 and 90° of flexion, in the form of 3 reciprocal concentric-concentric and 3 eccentric-eccentric cycles with a 15-second rest in-between trials. After a practice trial, the isokinetic contractions will be performed in a random order of mode (concentric v. eccentric) and angular velocities of 50, 100, 150, 200, and 250°/sec. In each case, the highest force of contraction among 3 attempts will be utilized to represent the peak isokinetic MVC at that speed.

**Knee Extensors**

Hand-held dynamometer protocol: Participant is placed in a seated position with their test leg in 90° of knee flexion. The dynamometer is placed over the anterior aspect of the participant's shank, just proximal to the ankle joint. The participant is instructed to extend their knee with maximal effort.

Isokinetic Dynamometer protocol: For isometric strength, the participants will be asked to perform a series of MVCs over a knee range between 10 and 90° of flexion, at 20° decrement (10, 30, 50, 70, and 90° of knee flexion) in a random order. After a practice trial, 3 attempts of 5-second MVCs will be allowed in each joint position with 15-second rest in-between trials. The highest force among 3 attempts will be utilized to represent the peak isometric MVC at that knee position. For isokinetic strength, the participants will be asked to perform a series of MVCs over a knee joint range between 10 and 90° of flexion, in the form of 3 reciprocal concentric-concentric and 3 eccentric-eccentric cycles with a 15-second rest in-between trials. After a practice trial, the isokinetic contractions will be performed in a random order of mode (concentric v. eccentric) and angular velocities of 50, 100, 150, 200, and 250°/sec. In each case, the highest force of contraction among 3 attempts will be utilized to represent the peak isokinetic MVC at that speed.
**Hip Extensors**

Participant is placed in a prone lying position (face down) with their test leg in 90° of knee flexion. The dynamometer is placed over the posterior aspect of the participant's thigh, just proximal to the knee joint line. The participant is instructed to extend their hip with maximal effort while keeping their knee in the flexed position.

**Hip Abductors**

Participant is placed in the supine position. The dynamometer is placed just proximal to the participant's lateral malleolus. The participant is instructed to abduct their hip with maximal effort.

**Hip External Rotators**

Participant is placed in a prone lying position (face down) with their test leg in 90° of knee flexion and neutral hip rotation. The dynamometer is placed over the medial aspect of the participant's shank, just proximal to the ankle joint. The participant is instructed to externally rotate their hip with maximal effort.

**Hip Internal Rotators**

Participant is placed in a prone lying position (face down) with their test leg in 90° of knee flexion and neutral hip rotation. The dynamometer is placed over the lateral aspect of the participant's shank, just proximal to the ankle joint. The participant is instructed to internally rotate their hip with maximal effort.

**Flexibility Tests**

Two trials of each flexibility test will be measured and the average value will be used for analyses. Researchers will establish good intrarater reliability with these measures prior to data collection.

**Gastrocnemius/Soleus**

Ankle dorsiflexion range of motion (ROM) will be assessed with the knee both extended and flexed to measure gastrocnemius and soleus muscle flexibility, respectively. Ankle dorsiflexion ROM will be measured with the knee extended and the participant in a supine position with a foam roller under the lower leg to maintain full knee extension. Ankle dorsiflexion ROM will be measured with the knee flexed will be assessed the same as knee extension but with the foam roller behind the knee to cause at least 30 degrees of knee flexion. For both tests, the digital inclinometer will be placed on the dorsal aspect of the foot. Passive ROM will be recorded at the position where resistance is felt by the research assistant.

**Knee Flexion and Extension**

Passive knee flexion range of motion will be assessed with the participant lying in a prone position on a table. Passive and active knee extension ROM will be assessed with the participant lying in a supine position on the table. A foam roller will be placed under the knee. Active ROM will require the participants to straighten their knee as much as they can. The digital
inclinometer will be positioned on the anterior lower leg for all measurements. Passive ROM will be recorded at the position where resistance is felt by the research assistant.

**Heel Height Differential**

Heel height differential will be assessed with the participant lying in a prone position on a table. Heel height difference will be assessed by measuring in centimeters the height of each heel with both the patellae on and off of the table. Difference in heel height will be divided by the length of the lower limb segment to determine degrees of flexion contracture in the knee.

**Joint Laxity Tests**

Joint laxity will be assessed using the Beighton and Horan Joint Mobility Index (BHJMI) and Tibial Translation via the KT-1000. The BHJMI takes less than 2 minutes to complete and consists of 5 tests performed bilaterally except for the trunk flexion test. The tests are on an ordinal scale, graded "0" if the criteria is not met and "1" if the condition is met. The five tests are:

1. **Fifth-finger extension** - the fifth finger is passively extended and if it is extended beyond $90^\circ$ then it is graded a 1.

2. **Wrist flexion and thumb opposition** - The participant will stabilize the distal portion of the forearm with the thumb of the opposite hand, and the thumb being tested will be passively abducted by the fingers of the opposite hand toward the volar aspect of the forearm with the wrist in flexion. If the thumb can touch the forearm then the score is 1.

3. **Elbow extension** - The shoulder is abducted to $80^\circ$ with the forearm supinated. The tester stabilizes the proximal forearm and applies gentle pressure on the wrist to achieve passive end range extension. The score is 1 if the elbow extends past $10^\circ$ of hyperextension.

4. **Knee extension** - Knee extension is conducted supine with a bolster placed under the ankles. A goniometer is placed at the knees and the participant is instructed to relax. The score is 1 if hyperextension is greater than $10^\circ$.

5. **Trunk and hip flexion** - The participant is standing with their knees extended or hyperextended and they are instructed to touch their palms to the floor. If they can touch their palms to the floor then the score is 1.

Finally, we will measure knee laxity using an instrumented knee arthrometer or KT-1000. The KT-1000 will be attached to the participant's lower leg using Velcro straps with the knee bent to $25-30^\circ$. One pad of the KT-1000 will be placed on the patella and the other on the tibial tuberosity. The participant will be asked to relax and the investigator will pull on the KT-1000 with 133-N of force in an anterior direction taking measurements of displacement by reading a dial on top of the KT-1000. This will be repeated 3 times on each leg. Three measurements will also be recorded with the investigator pushing in a posterior direction at 133-N.

**Functional Performance Tests**

**Single Leg Hop for Distance (3 repetitions)**

Participants will be instructed to stand on one leg, hop forward as far as possible off of this leg and land on the same leg. The distance traveled will be measured.
**Triple Hop for Distance (3 repetitions)**

Participants will perform three one legged hops for distance on the reconstructed and normal side. The three trials for each leg will be measured and recorded.

**Crossover Hop Test (3 repetitions)**

Participants will perform 3 one legged hops while alternately crossing a longitudinal marking placed on the floor. The total distance hopped forward is recorded.

**Six Meter Timed Hop Test (3 repetitions)**

Participants will stand on one foot and hop as fast as possible over a 6-meter marked distance. The time to complete task will be recorded to the nearest hundredth of a second.

**Treadmill Walk**

Subjects will be asked to complete a 5-minute warm up of walking at a self-selected comfortable pace. A rating of perceived exertion (RPE) scale that runs from 0-10 (No activity to very, very heavy activity) will be used to guide subjective exertion. Each subject will increase or decrease his or her walking speed until an RPE intensity level of "light" (2) to "moderate" (3) is reached. Following the 5-minute warm up, each subject will complete 10-20 minutes of walking at his or her self-selected pace.

**Treadmill Run**

Subjects that have been cleared for full activity participation will be asked to complete a 5-minute warm up at a self-selected pace. Following the warm up, each subject will complete 5-10 minutes of running at RPE activity level of "heavy" (5) to "very heavy" (7).

**Thigh Girth Measurement (2 repetitions)**

Participants will have the girth of both thighs measured at three standardized points using a cloth tape measurer. The three standardized points will be around the superior edge of the patella, 10 cm above the superior edge of the patella and 25 cm above the superior edge of the patella.

**Neural Excitability Tests**

**Quadriceps Activation Failure (central activation ratio)**

The isokinetic dynamometer (Biodex System 4, Biodex Medical Systems, Shirley NY) will be used to measure maximal voluntary force during the muscle activation testing. Participants will sit in the dynamometer and will be positioned in 85° of trunk flexion and 90° of knee flexion (45-47). Restrictive straps will be 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, will be secured to a pad on the arm of the dynamometer with Velcro straps. Participants will be instructed to cross arms over the chest during all contractions to avoid unwanted upper extremity involvement in the task (45-47). Two 7x13cm self-adhesive stimulating electrodes will be 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). Once correctly positioned in the
dynamometer, participants will be asked to perform a series of submaximal isometric quadriceps contractions in which they will attempt to extend their knee at 25, 50 and 75% of their perceived maximal effort. Additionally, participants will receive submaximal electrical stimulation at 25, 50 and 75% of the maximal 130 volts (100ms train of 10 stimuli, at 100 pps, with a pulse duration of 0.6 ms, and a 0.01 ms pulse delay via the Grass S48 dual channel electrical stimulation unit with an SIU8T isolation unit attached [Grass Products, Natus Neurology]) (45-47). Participants will then be asked to perform practice maximal contractions (without electrical stimulation) until the investigator is confident that a maximal effort is being put forth. Participants will then perform 3 maximal isometric contractions with visual feedback and verbal encouragement with 60 seconds between trials. When each participant reaches a plateau in torque output, the supramaximal electrical stimulation will be triggered, which will contract any muscle not voluntarily contracted by the participant. An increase in torque output following the electrical stimulation denotes the presence and magnitude of quadriceps activation failure. This procedure will be used to test both limbs and the order in which limbs are tested will be counterbalanced.

In order to quantify the amount of quadriceps activation failure, we will calculate the central activation ratio (CAR). To determine the CAR, the subject's peak torque generated immediately prior to the delivery of the electrical stimulus will be divided by the peak torque generated as a result of the electrical stimulus (superimposed burst torque) (Figure 2). A CAR of 1.00 will be accepted to represent complete quadriceps activation (2). (Approved by IRB Protocol H11-035).

**Hoffmann Reflex**

The Hoffmann Reflex is a measure of spinal cord output (e.g. spinal-reflexive excitability). Participants will be instructed to lie supine on a padded treatment plinth or stand with their arms comfortably placed at their side with their head in a neutral position. The head of each participant will rest comfortably on a pillow and their knees slightly flexed (~10-15º). The hair over the collection sites will be shaved and the skin over the recording electrode site will be debrided and cleaned with alcohol. Two 10mm, pre-gelled Ag-AgCl (EL503, BIOPAC Systems Inc.) surface electromyography (EMG) electrodes will be position 2cm apart over the muscle belly of interest. EMG signals will be band-pass filtered from 10 to 50 Hz and collected at 1024Hz with a common-mode-rejection ratio of 110 dB. A 2mm shielded disc stimulating electrode (EL2524S, BIOPAC Systems Inc.) will be positioned over the femoral nerve and secured with hypoallergenic tape and a 7x13cm self-adhesive electrode will be positioned over the hamstring and used as a dispersive electrode. A 1ms square wave stimulus will be 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 (23). (Approved by IRB Protocol H11-035).

During testing, participants will be instructed to maintain a constant head, eye and hand position by focusing on a circle on the ceiling. The stimulus will be increased in 2-volt increments until a maximum Hoffmann reflex is elicited, and then 3 maximal Hoffman reflexes will be collected at that voltage. The stimulus will be increased until a maximal muscle response is elicited, in which 3 maximal muscle responses will then be elicited. This procedure will be used to test both limbs and the order in which limbs are tested will be counterbalanced.

**Corticospinal Excitability Testing** (Note: These methods have been previously approved by the IRB for Protocol H15-294 & H).
Transcranial magnetic stimulation (TMS) will be used to determine the active motor threshold (AMT), amplitude of motor evoked potentials (MEP) elicited at 120% of AMT, and short interval intracortical inhibition (SICI) and intracortical facilitation (ICF). Two 10 mm, pregelled Ag-AgCl (EL503, BIOPAC Systems Inc., Goleta, CA, USA) disc shaped surface electromyographic (EMG) electrodes, with an inter-electrode difference of 1.75 cm, will be positioned over the distal belly of the vastus medialis and vastus lateralis muscles, when necessary. When necessary, the hair over the collection site will be shaved (Phillips Norelco electric razor) and the skin over the recording electrode site will be abraded and cleaned with alcohol by a researcher of the same gender.

Participants will be secured into a Biodex System IV Pro Dynamometer (Biodex Medical Systems, Shirley, New York, USA) with their knees and hips at 90° of flexion. Additionally, if the Biodex system is unavailable, muscle force production will be monitored via a handheld dynamometer (micro FET; Hoggann Scientific LLC, West Jordan UT). A Lycra swim cap, with a 0.5 cm grid, will be placed on the participant's head. The cap will be positioned by using straight lines drawn vertically in the sagittal (center of the occiput to the nose) and frontal planes (connecting each external auditory meatus), and allow for identification of the approximate motor cortex location. The swim cap will be machined washed in the Department of Kinesiology facilities between participant use. A double cone angled TMS coil (D-B80, MagVenture Inc., Atlanta, GA) will be positioned over the intersected lines and moved in increments of 0.5 cm in anterior-to-posterior and medial-to-lateral directions until the optimal stimulating point is detected, which is defined as the location producing the greatest MEP amplitude in the muscle of interest. The stimulator (MagPro R30 with Magoption, MagVenture Inc.) will be secured over that spot using a flexible mount (Super Flex Arm, MagVenture Inc.). Once the optimal stimulating point is located, the AMT will be determined. The AMT is defined as the lowest TMS intensity required to evoke a measureable (>100 μV) MEP in five out of 10 trials. Once AMT is established, eight MEPs will be elicited at 120% of AMT. The eight peak-to-peak MEP amplitude values will be averaged and normalized to the average of three maximal muscle responses elicited during Hoffmann reflex excitability testing.

A paired conditioning-test stimulus technique will be used to assess both SICI and ICF. During testing, a conditioning pulse will be set to 80% of AMT in order to provide a subthreshold stimulus to produce a short period of suppression in EMG activity. Physiologically, the subthreshold conditioning pulse reduces the amplitude of synaptically evoked corticospinal volleys through GABA-ergic connections (gamma-aminobutyric acid), resulting in synaptic inhibition of the corticospinal neurons that are targeted by a testing stimulus above the threshold level. SICI and ICF are thought to be mediated by GABA and NMDA (N-methyl-D-aspartate) receptors, respectively. Following the subthreshold stimulus, a subsequent testing stimulus of 120% of AMT will be given at a time of 3ms during SICI testing and 15ms during ICF testing. The time interval between stimuli determines the effect the conditioning pulse has on the measured MEP. Eight SICI and eight ICF MEPs will be evoked, normalized to raw MEP values at 120% AMT and averaged for analysis.

During all TMS testing, each participant will maintain an isometric contraction at 5% of their maximal voluntary isometric contraction (MVIC) and will be instructed to rest between stimuli.

**Electromyographic (EMG) Testing**
During the isometric and isokinetic knee extensor and flexor testing, movement tests and functional performance tests (described above), EMG signals will be collected in order to assess alterations in muscle activity. To record muscle activity, the skin for each electrode site will be shaved and cleaned with isopropyl alcohol. Surface EMG electrodes (Dual EMG Electrodes [4cm x 2.2cm], Noraxon Inc.) with a 1.75 cm inter-electrode distance will be secured over the muscle bellies of the vastus lateralis and the lateral hamstring according to the technique described by Delagi et al. (51),(9) Raw EMG data will be collected using a commercial EMG system (Desktop DTS, Noraxon Inc.) that will be sampled at 1500 Hz during knee extensor and flexor contractions. EMG signals will be band-pass filtered 6 to 1000 Hz and subsequently processed using a root-mean-square algorithm with a 50-millisecond moving window. Dynamic EMG collected during the contractions will be normalized to the peak muscle activity that occurs during testing. (Test approved by IRB Protocol H11-035).

Sonographic Assessment

To quantify quadriceps muscle architecture sagittal and transverse ultrasound images will be taken by a trained clinician using the Phillips, HD11 XE Ultrasound System at three sites along the length of each quadriceps muscle. Ultrasound sites will be based on the relative distances between the patella and the anterior superior iliac spine (e.g. patella-iliac distance). For the vastus medialis, the sites will be 5, 22 and 39%, for the vastus lateralis they will be 22, 39 and 56% and for the rectus femoris they will be 39, 56 and 73% of the patella-iliac distance. The vastus intermedius will be imaged at two distinct parts: the anterior vastus intermedius and lateral vastus intermedius. The anterior vastus intermedius will be imaged at 22, 39 and 56% and the lateral vastus intermedius will be imaged at 39, 56 and 73% of the patella-iliac distance (33, 41). At the end of imaging, the clinician will transfer the images to a CD so they can be examined later for possible structural abnormalities. (Approved by IRB Protocol H11-035).

Qualitative Interview

We aim to collect additional information pertaining to physical and psychological barriers individuals encounter following ACLR and subsequent recovery. For Aim 1 we aim to examine whether these individuals’ level of success on functional testing measures match their perceived success and satisfaction of attained physical function and return to sport status following ACLR. Additionally, for Aim 2 we aim to interview these participants two times both pre-surgery and post-operatively following clearance to return to sport. We aim to examine whether pre-surgery expectations regarding outcomes following ACLR matches the perceived level of success post-operatively following ACLR. These in-person interviews will occur as follows: for Aim 1 and 2 it will occur following the test battery of functional tests, for Aim 3 it will occur following the completion of functional tests for all Sessions. The interviews (see attached interview guide, Appendix) will be semi-structured, allowing for follow up on participant’s responses. We anticipate these interviews will last no longer than 25-30 minutes in length. For those participants under 18 a parent or guardian may be present during the interview. Interviews will be audio recorded and transcribed verbatim.

Following the qualitative interview, participants will be asked for their telephone number and/or preferred method of contact in the case a researcher required follow up on previous responses. Any responses or correspondences that contain sensitive information regarding the participants condition will be conducted via primary contact number/telephone to protect confidentiality.
Justification of Sample Size/Data Analysis: Justification of Sample Size: For qualitative and pilot studies, describe how the proposed sample size is appropriate for achieving the anticipated results. For quantitative studies, provide a power analysis that includes effect size, power and level of significance with references for how the sample size was determined. Explain the rate of attrition, with references as appropriate. Data Analysis: For all studies, provide a description of the statistical or qualitative methods used to analyze the data.

We estimated the sample size for this study via a power analysis using previous studies that have demonstrated clinically significant differences (large effect sizes > 0.7 and >20% differences) between individuals with and without a history of an ACL reconstruction (when available) and between individuals who returned and did not return to physical activity following ACLR.

Four key dependent variables related to return to sport and function following ACLR were analyzed for this power analysis: neuromuscular control (as measured by LESS, peak vertical ground reaction force (PVGRF), and knee valgus moment variables), muscle strength (as measured by hip abduction strength, quadriceps activation failure, knee extension strength, quadriceps EMG and Hoffmann reflex), "sport performance" (as measured by single limb hop distance) and subjective measures. For Aims 1 & 2, we utilized a previously approved IRB power analysis as a guideline for this study (protocol number H11-035). Additionally, an a priori power analysis utilizing previously published literature indicates that a sample size of 17 per group will be sufficient to detect significant differences in International Knee Documentation Committee (IKDC) scores between those who returned to sport and those who did not. An alpha level of significance = 0.05 and a desired power level of 0.8 were used for all analyses. Given, the demographic information regarding our previously collected participants indicates heterogeneity amongst individuals with a history of an ACL reconstruction (e.g. differences in time since surgery, age, and graft type), and some female participants may be excluded from the electrical stimulation measures due to pregnancy (or because they choose not to undergo the pregnancy test), we wish to increase the enrollment of participants with neuromuscular measure and a history of an ACLR by 30% (n=50 per group (returned or not returned to sport) in case any participant is unable to perform the entire test battery and also because several of the variables we are testing have not been studied previously in this population so a true estimate of the necessary effect size for these variables is unknown. Hence, in total we plan to recruit a total of 100 individuals with a history of ACL reconstruction. We believe this sample size will allow us to produce impactful contributions to the clinical literature and be within our current funding means. Additionally, we plan to screen a maximum 100 healthy controls to determine age, sex, activity level, height, mass and injury history. Personal schedule availability will also be a determining factor. Potential healthy participants will be screened to find similar matches to the ACL reconstructed individuals.

Additionally, we anticipate recruiting between 20 and 30 participants (for both aim 1 and aim 2) for the in-person interviews in order for us to reach data saturation. This sample size is justified by interviewing about 10 participants within each age group or until data saturation is reached. The age groups are defined as followed: 14-18, 19-25, 26-35.

For Aim 3 (longitudinal study), we will follow the results of the power analysis above and aim to recruit 50 participants.
For Aim 1 we will analyze the data utilizing regression analyses to test the hypothesis that common barrier and facilitator themes identified through qualitative interviews will be negatively and positively related to physical function, respectively. We expect to find that barrier themes will negatively influence physical function and that facilitators will positively influence physical function. To further examine how themes identified through qualitative interviews affect physical function, we will dichotomize participants who returned to pre-injury level of sport and those who did not (determined by their pre-injury Tegner score) and perform additional regression analyses. Lastly, independent t-tests will be performed to detect differences in muscle strength, functional performance, movement tasks and neuromuscular function between groups.

For Aim 2 we will use a mixed methods approach to test our hypothesis. Specifically, we will quantitatively test the hypothesis that perception of success, as measured by the total score on the K-SES and ACL-RSI scale, is not predictive of physical activity participation (Tegner activity scale, KOOS subscales) and physical function (muscle strength, functional performance measures) using regression analyses. Based on participant’s answer to the question "Do you believe your ACLR was successful in returning your physical function, yes or no?", conducted during the qualitative interview, we will also dichotomize participants into two groups: those that answer 'yes' and believe their physical function is restored and those that answer 'no'. Additional regression analyses will then be performed to qualitatively determine if individual perception of success is related to physical activity participation and physical function.

For Aim 3 multiple regressions will be utilized to examine the relationships between 1) pre-surgical psychological readiness (as measured by the ACL-RSI scale) and post-surgical psychological readiness, 2) pre-surgical physical function and post-surgical physical function, 3) pre-surgical psychological readiness and post-surgical physical function, and 4) pre-surgical physical function and post-surgical psychological readiness. To further examine how pre-surgical function affects post-surgical outcomes, participants will be split into groups of 1) high pre-surgical psychological and high physical readiness [determined by 5159 cutoff score on ACL RSI scale and a quadriceps strength [normalized to body mass] cutoff score of 3.10 Nm/kg], 2) low pre-surgical psychological and low physical readiness, 3) high pre-surgical psychological and low pre-surgical physical readiness and 4) low pre-surgical psychological and high physical readiness. One-way ANOVAs will then be conducted between groups to determine how pre-surgical function affects post-surgical outcomes. Additionally, one-way ANOVAs will be conducted between ACLR and healthy control groups for Aims 1-3 to determine group differences in physical and perceived function.

The alpha level for all statistical tests will be set at P<0.05 and statistical test will be analyzed using SPSS.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group 1 Mean±SD</th>
<th>Group 2 Mean±SD</th>
<th>Sample size estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>LESS (pts)(12)</td>
<td>5.40±2.10 (before ACL IPP)</td>
<td>4.00±1.70 (after ACL IPP)</td>
<td>23</td>
</tr>
<tr>
<td>Peak VGRF (%BW)(20, 50)</td>
<td>4.53±1.51 (before ACL IPP)</td>
<td>3.57±1.10 (after ACL IPP)</td>
<td>24</td>
</tr>
<tr>
<td>Knee valgus moment (N/kg*m)(40)</td>
<td>3.40±1.60 (before ACL IPP)</td>
<td>2.10±1.00 (after ACL IPP)</td>
<td>13</td>
</tr>
<tr>
<td>Test</td>
<td>Mean ± SD (Sample)</td>
<td>Mean ± SD (Sample)</td>
<td>Test</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>--------------------------------------------</td>
<td>--------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Hip abduction/adduction displacement(10)</td>
<td>5.04±6.03 (ACL Recon)</td>
<td>9.04±5.87 (ACL Recon)</td>
<td>27</td>
</tr>
<tr>
<td>Knee flexion displacement(10)</td>
<td>42.66±9.29 (ACL Recon)</td>
<td>51.40±7.62 (ACL Recon)</td>
<td>15</td>
</tr>
<tr>
<td>Gluteus medius strength (N/kg)(22)</td>
<td>4.77±1.03 (before ACL IPP)</td>
<td>6.46±0.98 (after ACL IPP)</td>
<td>4</td>
</tr>
<tr>
<td>Single leg hop for distance(37)</td>
<td>173.6±27.9 (ACL Recon)</td>
<td>187.7±28.7 (healthy)</td>
<td>5</td>
</tr>
<tr>
<td>Quadriceps activation failure (central activation ratio)(31)</td>
<td>91.8±4.6 (ACL Recon)</td>
<td>96.6±2.8 (healthy)</td>
<td>32</td>
</tr>
<tr>
<td>Knee extension strength (Nm/kg)(31)</td>
<td>2.1±0.6 (ACL Recon)</td>
<td>3.1±0.9 (healthy)</td>
<td>28</td>
</tr>
<tr>
<td>Electromyographic muscle activity (mV)(13)</td>
<td>0.5±0.2 (ACL Recon)</td>
<td>0.9±0.2 (healthy)</td>
<td>12</td>
</tr>
<tr>
<td>Hoffmann reflex(48)</td>
<td>0.24±0.09 (ACL Recon)</td>
<td>0.28±0.11 (healthy)</td>
<td>6</td>
</tr>
<tr>
<td>International Knee Documentation Committee Subjective Form (IKDC) (Lentz, 2012)</td>
<td>93.8±6.3 (ACL Recon Returned to Sport)</td>
<td>78.0±15.6 (ACL Recon Did Not Return to Sport)</td>
<td>17</td>
</tr>
</tbody>
</table>

Qualitative methodology guided by the phenomenological approach will be used to analyze the three different aims of the study. We will utilize this methodology to gain a greater understanding how barriers and facilitators influence patient self-reported outcomes and physical measures, whether an individual's perception of success after ACLR matches the level of physical activity participation and physical and whether an individual's pre-surgery expectations differ from perceptions of success following ACLR. Phenomenology attempts to provide a description of a particular phenomenon of interest by gathering 'rich information' through the use of semi-structured interviews and participant observation and by reducing each individual's experiences into a universal principle61,62. Utilizing a phenomenological approach provides the researchers the opportunity to understand the perceptions and needs of individuals, in this case athletes recovering from ACLR, as they complete their rehabilitation programs and return to pre-injury sport participation. This type of qualitative research methodology is pertinent when examining how an individual's environment shapes their perceptions of a particular construct. When analyzing the qualitative data, we plan to analyze the data by three separate age groups (ages 14-18 (adolescents), 19-25 (young adults), 26-35 (adults)) to ensure that the analyses and results accurately represent the age group of the participants. ACL injuries are most prevalent in the adolescent aged individuals and their experiences and responses will differ from young adults and further from adults who sustain and undergo ACLR.

The integration of the quantitative and qualitative data analyses will be performed by the three team members. When using multiple data sources and types (quantitative and qualitative), the most appropriate model for data integration/analysis is parallel mixed analysis or concurrent triangulation strategy62 which has two main benefits: 1) use of multiple methods (interviews, focus groups) offsets inherent weaknesses of each independent method when attempting to
confirm/corroborate findings; and, 2) interpretation of data across methods is enhanced by identifying and explaining convergence or divergence in the findings. These data will also provide richness and detail to the quantitative data.

Inclusion/Exclusion Criteria: [List major inclusion and exclusion criteria. Any proposed exclusion criterion based on gender (women of childbearing potential), age, or race must include justification for the exclusion. Describe the conditions under which participants may be removed from the study, i.e., noncompliance with study rules, study termination, etc.]

Please note: All of the above listed specific landing, cutting activities and strength testing measures are performed throughout the ACL rehabilitation protocol, therefore performing them during the specified testing sessions is not contraindicated. Prior to beginning the study, patients will be asked if they have performed the activities in their rehabilitation programs (ACL reconstruction exclusion checklist). If not, they will be subsequently excluded from the study.

Criteria for inclusion for ACL reconstruction for Phase 1 (Session 1 of Aim 3):
- Within the ages of 14-35
- Sustained a primary ACL injury within the past 12 months
- Ability to understand and speak the English language in order to participate in interviews

Criteria for inclusion for ACL reconstruction for (Aim 1, Aim 2 and Session 2 of Aim 3:
- Within the ages of 14-35
- Required to have returned to activities since their surgery
- Cleared by their physician to return to their pre-injury level of participation
- Ability to understand and speak the English language in order to participate in interviews

Criteria for exclusion for ACL reconstruction:
- Previous history of knee surgery other than the current ACL reconstruction
- A contralateral lower extremity injury suffered within the past 6 months
- Pregnant females
- Demand-type cardiac pacemaker
- An allergy to adhesive
- Open skin lesions or active skin infections (i.e. MRSA)
- Concussion or head injury in the past 6 months, or previous loss of consciousness with concussion injury.
- History of stroke, cardiac condition, epilepsy, seizures, cranial neurosurgery, migraines, cancer in the brain, diagnosed psychiatric or neurological disorder
- Currently taking medications that alter neural activity (antidepressants, antipsychotics)
- Intracranial metallic clips

Criteria for inclusion for healthy controls:
- Within the ages of 14-35
- Healthy, physically active individuals

Criteria for exclusion for healthy controls:
- Previous history of knee surgery
- A lower extremity injury suffered within the past 6 months
- Any subject currently suffering from knee pain
• Pregnant females
• Demand-type cardiac pacemaker
• An allergy to adhesive
• Open skin lesions or active skin infections (i.e. MRSA)
• Concussion or head injury in the past 6 months, or previous loss of consciousness with concussion injury.
• History of stroke, cardiac condition, epilepsy, seizures, cranial neurosurgery, migraines, cancer in the brain, diagnosed psychiatric or neurological disorder
• Currently taking medications that alter neural activity (antidepressants, antipsychotics)
• Intracranial metallic clips

Risks and Inconveniences: [Describe the potential risks to participants (and secondary participants, if applicable) and steps taken to minimize risks. Assess the likelihood of the risk occurring and, if it were to occur, the seriousness to the participant. Types of risks to consider include: physical, psychological, social, legal, employment, and financial. Also describe any anticipated inconveniences the participants may experience (time, abstention from food, etc.).]

This study involves minimal risks to the participants. The research assistants collecting this data are all certified athletic trainers or athletic training/physical therapy students who will be trained to minimize risks. The participants will be instructed that they may choose to not complete a task if they are not comfortable with the task. The research assistants will monitor testing procedures as well as provide verbal instructions to ensure that participants understand all testing procedures.

The following are a list of possible risks for participants in this study:

• The stimuli delivered during the neural excitability tests (quadriceps activation failure and the Hoffmann Reflex) are short but intense and subjects may experience some mild discomfort during testing.

• In order to make the stimuli as comfortable as possible, large pads will be used to apply the treatments.

• Participants may develop transient headaches during TMS testing, although this is rare.

• In participants with a history of epilepsy, TMS testing has a slight possibility of producing seizures, and therefore participants with epilepsy or any history of seizures will be excluded.

• It is also possible that participants might experience muscle soreness after the strength and activation testing because of repeated muscle contractions. These effects will not be significantly greater than that which they may experience in response to starting a new exercise regime.

• Participants will be asked to perform tasks that involve jumping, running, and cutting. Even though the tasks are common to sports, they may involve the risk of injuries to muscle, cartilage, ligaments, or bones in the participants' lower body.

• Also, there may be uncommon or previously unknown risks that might occur.
A potential inconvenience to this study is the participants will volunteer approximately 1.5 hours of their time to participate in this study.

All females who are willing to undergo electrical stimulation testing will undergo a pregnancy test (detailed above) to ensure they are not pregnant. The rationale behind excluding pregnant females is that the electrical stimulation measures that we are employing to assess muscle function in this study are contraindicated during pregnancy. It is important to note, that therapeutic electrical stimulation is often delivered during pregnancy as a treatment for low-back pain, and has been shown to be safe (protocol number H11-035). However, given that we are not providing a therapeutic dose of electrical stimulation, but rather a stimulus to detect for abnormalities in muscle activity, pregnant females will be excluded from procedures with electrical stimulation.

Participants may experience mild skin irritation due to skin preparation and the need to remove hair from the surface EMG and ultrasound measurements sites.

No significant potential risks are anticipated for participants involved in interview portion of this study. However, patients will be providing information about their decision-making relative to their rehabilitation and return-to-sport experience after undergoing anterior cruciate ligament reconstruction. Minimal potential risk exists that information from interviews could trigger past emotions about returning to sport or injuring their knee.

Benefits: [Describe anticipated benefits to the individual participants. If individual participants may not benefit directly, state so here. Describe anticipated benefits to society (i.e., added knowledge to the field of study) or a specific class of individuals (i.e., athletes or autistic children). Do not include compensation or earned course credits in this section.]

The test session will have no direct benefit on the participants, but may greatly assist with benefitting society, especially active and athletic individuals as well as healthcare clinicians. Knowledge about if adherence factors identified in rehabilitation may influence physical function and return to sport outcomes can help us individualize rehabilitation experiences in hopes of increasing numbers of individuals returning to sport following ACL reconstruction.

Risk/Benefit Analysis: [Describe the ratio of risks to benefits. Risks to research participants should be justified by the anticipated benefits to the participants or society. Provide your assessment of anticipated risks to participants and steps taken to minimize these risks, balanced against anticipated benefits to the individual or to society.]

The risks associated with this study are minimal and participants may choose to not complete a task if they are not comfortable with the test. Therefore, we believe the potential benefits to society, including a greater understanding of perceived barriers to rehabilitation adherence and factors influencing return to sport in conjunction with functional outcomes, justify the less than minimal risk to the participants. Certified athletic trainers will be present during all test sessions to ensure participants' risk is minimized to the maximum amount possible.

Economic Considerations: [Describe any costs to the participants or amount and method of compensation that will be given to them. Describe how you arrived at the amount and the plan for compensation; if it will be prorated, please provide the breakdown.]
Experimental or extra course credit should be considered an economic consideration and included in this section. Indicate when participants will receive compensation.

The only cost to the participants is their time. They will receive feedback about their movement technique following the test session if they wish. Those who participate in the longitudinal study (Aim 3) of this study will be compensated a total of $90 at the completion of the third and final testing session, if all three testing sessions are completed.

Data Safety Monitoring

This is a prospective plan set up by the study investigators to assure that adverse events occurring during studies are identified, evaluated, and communicated to the IRB in a timely manner. Although the investigators initially propose a Data Safety Monitoring Plan (DSMP), the IRB must approve the plan and may require revision of the plan. A DSMP is required for all human studies at the University of Connecticut except for studies determined to be exempt from continuing IRB review. For studies that present more than minimal risk to participants, the IRB will review and determine on a case-by-case basis whether a data safety monitoring board is most appropriate. Please refer to the IRB's policy regarding data safety monitoring before completing this section - http://irb.uconn.edu/irb_sop/IRBSOP_submission.html#data_safety_monit.

- Issues that should be addressed in the DSMP include the following:
  - frequency of the monitoring
  - who will conduct the monitoring (Under UConn policy a student cannot be the sole person responsible for monitoring the data and safety of the protocol procedures)
  - what data will be monitored
  - how the data will be evaluated for problems
  - what actions will be taken upon the occurrence of specific events or end points
  - who will communicate to the IRB and how communication will occur

Sample response to issues listed above for minimal risk/slight increase over minimal risk - "Survey results will be monitored by the PI in conjunction with the student investigator once every two weeks (items 1, 2 and 3). Survey responses will be reviewed to monitor for clarity (i.e., the same question is skipped by 5 or more participants). In that case, the question will be revised and an amendment will be submitted to the IRB (items 4, 5 and 6)."

Researchers will monitor all of the collected data once every week (items 1, 2, and 3). Responses on all of the questionnaires will be reviewed to monitor for clarity. If a situation arises that the same question is skipped by 5 or more participants, the question will be revised and an amendment will be submitted to the IRB. The data will be reviewed for completion to ensure the majority of the participants are able and willing to complete the requested tasks. If more than 5 participants are unable to complete the task or choose not to participate in that task, the task will be revised and an amendment will be submitted to the IRB.

The sonographic assessment is not a clinical assessment and findings will be solely used for research purposes related to this study. Therefore, any information or incidental findings following the sonographic assessment will not be disclosed to the participant or treating physician, with the exception that the physician is examining the images.
Researchers will notify parents of any child if there has been an adverse event. The PIs will complete an adverse event report if any injuries occur during the data collection. All members of the research team are certified in first aid and there will always be a certified athletic trainer present. The research team will provide basic first aid to any injury that may occur and will notify the team coach and parents about the injury.

Researchers will pilot the interview guide(s) with two participants prior to the start of recruitment to identify problems related to the questions being asked. This allows the opportunity to identify problems related to the interview guide, make any necessary changes and submit an amendment to the IRB.

The interview audio files and any transcripts will be stored on the researcher's password protected computer. Once interviews are transcribed, the transcripts will be identified only by an assigned pseudonym, not the participant's real name to protect their identity. At any time, if updates or issues arise during the data collection procedures, which warrant changes, the PI will submit an amendment to the IRB.

Privacy/Confidentiality

Explain how the privacy interests of participants will be maintained during the study (note that privacy pertains to the individual not to the data). Describe procedures for protecting confidentiality of data collected during the study and stored after study closure. Describe how data will be coded. Describe plans for storage and security of electronic data (plan must comply with the University’s Policy on the Security Requirements for Protecting University Data at Rest). If identifiable, sensitive information (illegal drug use, criminal activity, etc.) will be collected, state whether a Certificate of Confidentiality will be obtained. Be sure to state whether any limits to confidentiality exist and identify any external agencies (study sponsor, FDA, etc.) that will have access to the data. If participants will be screened, describe the plans for storage or destruction of identifiable data for those that failed the screening.

The following procedures will be used to protect the confidentiality of the data collected from the participants. Participants will not be identified in any report, presentation, or publication about this study. Participants will be assigned an identification number (ID) for data collection. This ID number will be the only identifier on all questionnaires, data and videos used for data collection in this study. The researchers will keep all study records locked in a secure location. A master key that links names and codes will be maintained in a separate and secure location. The master key and videotapes will be destroyed after 3 years. All electronic files (e.g., database, spreadsheet, etc.) containing identifiable information will be password protected. Any computer hosting such files will also have password protection to prevent access by unauthorized users. Only the principal investigator will have access to the passwords. Data that will be shared with others will be coded as described above to help protect the participants' identity.

To respect privacy and protect confidentiality, all participants who participate in the interview process will be identified by a pseudonym. The pseudonyms will be kept on a master list that will be in its own file separate from the data information. They will only be referred to by the pseudonym during transcription, data analysis, and in publication. All data, information, and pseudonym link will be maintained for a maximum of three years then all data will be deleted once the study is complete.
Informed Consent

As PI, you are responsible for taking reasonable steps to assure that the participants in this study are fully informed about and understand the study. Even if you are not targeting participants from "Special Populations" as listed on page 4, such populations may be included in recruitment efforts. Please keep this in mind as you design the Consent Process and provide the information requested in this section.

Consent Setting: [Describe the consent process including who will obtain consent, where and when will it be obtained, and how much time participants will have to decide. Describe how the privacy of the participants will be maintained throughout the consent process. State whether an assessment of consent materials will be conducted to assure that participants understand the information (may be warranted in studies with complicated study procedures, those that require extensive time commitments or those that expose participants to greater than minimal risk).]

Participants will meet with the principal investigators to pick up the consent form (assent form if needed), questionnaires, and surgical report form. At this time, a principal investigator will go over the consent (and assent form if needed) with the participants. The participants will take all forms home with them and will be instructed to contact the principal investigator if he/she has any questions or concerns. Additionally, for all potential female participants, the principal investigator will inform all individuals (and legal guardians when applicable) about the need to screen for potential pregnancy at the testing appointment. In accordance with the recommendations made by the IRB, legal guardians will be told that the result of the pregnancy test will only be shared with the minor and it will be at the minor's discretion of whether or not to share this test result with their legal guardians. Potential participants will also be informed that in the case of suspected child abuse, the appropriate authorities will be contacted by the principal investigator to ensure the safety and well-being of the child. Participants will have at least a week to think about their participation in the study. The participants will bring all completed forms with them to the testing session. If the legal guardian is not present at the time of delivery of the forms (when applicable), they will be encouraged to contact the principal investigator with any questions or concerns regarding the study. Participants (and their legal guardians) will be instructed that the principal investigator will be present when they arrive for the test session if they have any remaining questions or concerns prior to participating in the study. After the participants sign the consent form, a copy will be given to them if they desire. The voluntary nature of participation and the fact that the choice to participate and the information gathered in the study will have no effect on medical care will be included on the consent forms and will be verbally reviewed with every participant.

Capacity to Consent: [Describe how the capacity to consent will be assessed for participants with limited decision-making capacity, language barriers or hearing difficulty. If a participant is incapable of providing consent, you will need to obtain consent from the participant's legal guardian (please see the IRB website for additional information).]

All participants under the age of 18 will be required to have a parent or legal guardian's signature on the consent form in order to participate in this investigation. The consent form is attached.
Parent/Guardian Permission and Assent: [If enrolling children, state how many parents/guardians will provide permission, whether the child's assent will be obtained and if assent will be written or oral. Provide a copy of the script to be used if oral assent will be obtained.]

One parent/guardian will provide permission. Child's written assent will also be obtained.

Documentation of Consent: [Specify the forms that will be used for each participant population, i.e., adult consent form, surrogate consent form, child assent form (written form or oral script) or an information sheet. Copies of all forms should be attached to this application in the same format that they will be given to participants (templates and instructions are available on the IRB website).]

A parent permission form will be used for all participants under the age of 18. Children under the age of 18 will sign the parent permission form as well as the parent. Participants 18 years or older will sign the consent form.

Waiver or Alteration of Consent: [The IRB may waive or alter the elements of consent in some minimal risks studies. If you plan to request either a waiver of consent (i.e., participants will not be asked to give consent), an alteration of consent (e.g., deception) or a waiver of signed consent (i.e., participants will give consent after reading an information sheet), please answer the following questions using specific information from the study:]

Non-applicable.

Waiver (i.e. participants will not be asked to give consent) or alteration of consent (e.g. use of deception in research):

Why is the study considered to be minimal risk?

How will the waiver affect the participants' rights and welfare? The IRB must find that participants' rights are not adversely affected. For example, participants may choose not to answer any questions they do not want to answer and they may stop their participation in the research at any time.

Why would the research be impracticable without the waiver? For studies that involve deception, explain how the research could not be done if participants know the full purpose of the study.

How will important information be returned to the participants, if appropriate? For studies that involve deception, indicate that participants will be debriefed and that the researchers will be available in case participants have questions.

Waiver of signed consent (i.e. participants give consent only after reading an information sheet):

Why is the study considered to be minimal risk?

Does a breach of confidentiality constitute the principal risk to participants? Relate this to the risks associated with a breach of confidentiality and indicate how risks will be minimized because of the waiver of signed consent.
Would the signed consent form be the only record linking the participant to the research? Relate this to the procedures to protect privacy/confidentiality.

Does the research include any activities that would require signed consent in a non-research setting? For example, in non-research settings, normally there is no requirement for written consent for completion of questionnaires.
IRB References:


APPENDIX F

Institutional Review Board Consent Form

Consent Form for Participation in a Research Study

UCONN UNIVERSITY OF CONNECTICUT

Principal Investigator: Lindsey K. Lepley, PhD, ATC
Student Researcher: Julie P. Burland, MS, ATC, CSCS
Study Title: Examining Barriers, Facilitators and Physical Function in Individuals Following Anterior Cruciate Ligament Reconstruction.

Introduction

You are being invited to take part in a research study about examining factors that influence functional outcomes following anterior cruciate ligament (ACL) surgery. You are being invited to take part in this study because you either have 1) sustained an ACL injury, 2) plans to undergo ACL reconstruction surgery and/or underwent anterior cruciate ligament reconstruction (ACLR) at least 6 months ago, 3) have been cleared by your treating physician 4) are able to provide information about your recovery experiences and if you chose to return or not return-to-sport, and you 5) are without any history of surgery to your opposite knee, ankle, leg, or hip or injury to either involved knee, ankle, leg or hip within the last 6 months. You are being invited to participate in this study because it is unclear why many of ACLR patients are not returning to sport and what functional problems may remain following ACLR. If you volunteer to take part in this study, you will be one of about 100 people to do so.

Why is this study being done?

We are conducting this research study in order to learn about factors that may affect a person’s recovery experience as well as looking at the level of knee and physical function regained following ACLR. By conducting this study, we hope to further examine and learn about factors that affect an individual’s recovery experience and physical outcomes.

What are the study procedures? What will I be asked to do?

If you choose to participate in this study, you will be asked to complete up to three 120-minute test sessions on a specified date. The test session(s) will take place in the Human Performance Laboratory at the University of Connecticut. Before the test session(s), you will complete eight brief questionnaires:

1. Baseline questionnaire: Inquires about what sports you play currently and have played in the past, as well as information about whether or not you have ever sustained an injury to the lower body from sport participation that caused you to not be able to participate in sports for at least one day. Information about your rehabilitation will also be asked.
2. International Knee Documentation Committee (IKDC) Participant Knee form: Asks about your current knee function
3. Knee Injury and Osteoarthritis Outcome Score (KOOS) form: Asks about your
4. Anterior Cruciate Ligament Return to Sport after Injury (ACL-RSI) form: Asks about your psychological thoughts about your knee and physical activity.

5. Tegner/Lysholm activity rating scale: One copy of this form will be completed about your current level of activity and a second copy will be completed about your activity level prior to injury.

6. Tampa Scale of Kinesiophobia (TSK): Asks about your feelings about playing sports and getting injured.


8. Learned Helplessness Scale(s) (LHS): Asks about how you feel with regards to performing specific physical tasks.

9. Veterans Rand 12 (VR-12) and Short Form 36 (SF-36): Asks about how you feel about your quality of life.

10. Single Assessment Numeric Evaluation (SANE): Asks one question about how you feel about your physical function.

11. The Laterality Preference Index (LPI): Asks you about which limb you prefer to use during specific tasks.

12. Exclusion criteria checklist, to ensure you meet all the pre-screening criteria to be included in this study.

***Female Participants Only*** In order to ensure you meet all pre-screening criteria, we need to conduct a pregnancy test to ensure you are not pregnant. We are doing this because some of the electrical stimulation measures involved in this study are potentially harmful to a developing fetus and we want to ensure your safety. The results of this test will be kept in a locked research office and will not be shared with anyone outside of the research team. If you have a positive test result, in a private setting the principal investigator will inform you of this, and will hand you a list of local resources that you may use at your own discretion. It will be your decision whether or not to share this information with your parents. In the case of a positive test, the principal investigator will notify your pediatrician so that they can provide immediate counseling and follow-up care for you. If you choose not to take the pregnancy test, and you meet all other inclusion criteria, you may still be involved in this study and will not undergo electrical stimulation testing measures. If you are willing to undergo electrical stimulation muscle testing, the pregnancy test (urine sample) will be performed onsite in the Human Performance Laboratory prior to any other testing according to the manufacturer’s instructions.

When you arrive for the test session, you will listen to instructions about what will happen during the study to ensure you still want to participate and have indicated this on this form. You will have your height and weight measured and recorded. You will then perform a standardized warm-up consisting of jogging and performing any stretches that you wish. You will perform movement, balance, performance, strength, neural control, range of motion, and joint laxity tests in a random order during the test session. You will receive instruction and see a demonstration of each of the tests followed by as many practice trials as you would like in order to feel comfortable with the tests and perform them correctly. You may not be asked to perform all of the tasks described below due to time or the history of your knee injury.

Movement Tests
Participants who have been released back to full activity will be asked to perform the following performance tests.

You will be asked to perform 5 movement tests in a random order: Double-Leg Squat, Single-Leg Squat, Jump-Landing, Sidestep Cut, and Balance. Six sensors will be placed and secured to your upper back, lower back, thighs, and lower legs before any of these tests. These sensors passively transmit information to a computer about the location and movement of your body. These sensors will not hurt you. Two standard digital video cameras will also record each movement test. One camera will be located in front of you and the other camera will be located to the right of your body.

**Double-Leg Squat**
You will begin the Double-Leg Squat with your feet shoulder-width apart, your arms extended straight over your head, and knees and hips straight. You will be instructed to squat down as if you were sitting in a chair and return to the starting position.

**Single-Leg Squat**
This task is identical to the Double-Leg Squat except that it is performed on a single leg and with hands on hips.

**Jump-Landing Test**
You will begin the jump-landing test standing on a box 1-foot high and will jump off the box forward towards a force plate that is placed half your height away from the box. You will be instructed to immediately jump as high as you can after you land. (Figure 1)

**Sidestep Cut**
You will jump forward and down off of a 1-foot high box a distance of half your body height, land with your foot on a force plate, and perform a sixty degree cut towards your other side.

**Balance**
You will stand on a 1-foot high box a distance of half of your body height away from a force plate. You will jump forward from the box off of your non-dominant foot and land with your dominant foot in the center of the force plate while maintaining your hands on your hips and your non-dominant foot off of the ground. You will be instructed to balance as quickly as possible without putting your non-dominant foot down and remain in a single-leg stance for 10 seconds.

**Clinical Balance Tests**
**Balance Error Scoring System (BESS):**
You will stand with your eyes closed and hands on hips during two stances on two different surfaces (firm or foam) for both legs. You will stand on one foot with your other hip flexed 30 degrees and knee flexed 45 degrees for the Single leg stance. You will stand with the heel of one foot touching the toes of the other foot during the Tandem Stance. You will be instructed to stand in the stance as still as possible for 20 seconds during each stance.
**Y-Balance/Modified Star Excursion Balance Test**

You will balance on one leg while reaching for maximal distance with the other leg in three directions, which are indicated by tape on the ground. You will start with both feet in the center of the star and must keep your hands on your hips, your stance foot in the same position, and your stance heel on the ground while you perform the test. You will complete four practice trials in each direction followed by three test trials on both legs.

**Functional Performance Tests**

Participants who have been released back to full activity will be asked to perform the following performance tests.

**Single Leg Hop for Distance**

You will be instructed to stand on one leg, hop forward as far as possible off of this leg and land on the same leg. The distance traveled will be measured.

**Triple Hop for Distance**

You will be asked to perform a three one legged hops for distance on the reconstructed and normal side. Three trials for each leg are recorded and averaged. A ratio of the index to normal knee will be calculated.

**Crossover hop test**

You will be asked to perform 3 one-legged hops while alternately crossing a longitudinal marking placed on the floor. The total distance hopped forward is recorded.

**Six Meter Timed Hop Test**

You will stand on one foot and hop as fast as possible over a 6 meter marked distance. The time will be recorded to the nearest hundredth of a second.

**Strength Tests**

A hand-held dynamometer is a small instrument that can measure how hard you can push against it. This hand-held dynamometer will be used to measure the strength of six different muscles in the legs: knee flexors (hamstrings), knee extensors (quadriceps), hip abductors, hip extensors, hip internal rotators, and hip external rotators. You will receive instructions about how to perform each strength test and then will practice the tests until you feel comfortable with the tests. Two repetitions of each test will be performed on each leg. The dynamometer will also be used to assess the weight of each of your lower limbs, which will require you to relax your heel on the dynamometer while laying down on a table. Additionally, for knee flexor (hamstring) and knee extensor (quadriceps) strength testing you will be asked to sit in a chair attached to the device with your knees bent. Once you are positioned in the device, you will be asked to kick your leg out and pull your leg back against a pad as hard as you can. You will receive instructions about how to perform these strength tests and you will be allowed as many practice tests as needed until you feel comfortable with the tests. During these tests electrodes will be placed over your thigh muscles to assess for changes in muscle activity. Three repetitions of each test will be performed on each leg.
**Range of Motion Tests**
Your range of motion will be evaluated for 3 movements using a digital device (inclinometer). We will test how far you can pull your foot towards your body with your knee straight and bent, and test how far you can bend and straighten your knee. Two repetitions of each test will be performed.
We will also assess for the presence of a heel height differential using a goniometer.

**Joint Laxity Tests**
You will complete two joint laxity tests. The first one evaluates joint laxity throughout your body and involves five tests:

1. Fifth-finger extension – the fifth finger is passively extended and the amount of extension will be measured.
2. Wrist flexion and thumb opposition – You will try to touch your forearm with your thumb of the same arm.
3. Elbow extension – you will straighten your arm as much as possible and the amount of extension will be measured.
4. Knee extension – you will sit with a bolster under your ankles. You will be instructed to relax and the amount your knees straighten (extend) will be measured.
5. Trunk and hip flexion – You will stand with your knees extended and you will be instructed to try to touch your palms to the floor.

The second test is performed using a device that measures very small motion within the knee joint. You will lay on your back and bend your knee. The device will be attached to your lower leg with Velcro straps. You will be instructed to relax while a research assistant pulls on the device. Three repetitions will be performed on each leg.

**Thigh Girth Measurement**
The girth of both your thighs will be measured at three different points using a cloth tape measurer.

**Measures of Muscle Activity**:
Two large pads will be placed on the front of both of your thighs. Once all of the pads are attached to your leg, you will be positioned in a device that measures muscle strength. You will be asked to sit in a chair attached to the device with your knees bent. Once you are positioned in the device, you will be asked to kick your leg out against a pad as hard as you can. As soon as you feel comfortable with the kick, the researchers will apply a group of electrical stimulations to the skin of your thigh while you are resting. In order to help you get use to the stimulations, we will start giving them to you at a low level and will then increase the level in small amounts. We eventually need the level of the stimulations to reach 130 volts each (if these stimulations were delivered separately they would feel like a shock of static electricity like when you walk across a carpet and touch a door knob, except a shock of static electricity can reach up to 1,000 volts) The series of 10 stimulations will last less than 1 second and are delivered very close together, so you shouldn’t be able to feel individual stimulations. The group of stimulations will allow your muscle to contract even when you are resting. These stimulations may be slightly uncomfortable; the discomfort you experience in the muscle is normal. If at any time during the procedures you
feel as if the stimulations are too strong and you don’t want to continue, please notify the researchers immediately. Once you are comfortable with the stimulations, you will again be asked to kick out as hard as you can. Once the researchers see that you are contracting as hard as you can by watching the computer screen (usually in about 2 seconds), they will deliver the series of stimulations on top of your muscle. This technique, where we deliver stimulations on top of a muscle contraction, will be repeated 3 times for each leg.

**Measure of Spinal Cord Output:**
For these tests we will obtain measures of spinal cord function known as the H-reflex and M-wave. To obtain the H-reflex and M-wave one small area, on both legs, will be shaved, rubbed gently with sand paper, and cleaned with isopropyl alcohol. Four round stickers (electrodes) will be applied to this area and an additional electrode will be applied to the bone on the inside of your ankle. Next, you will be given a small round disc to place near your groin. A diagram will be provided to demonstrate the correct placement. Additionally, we will ask you to place a large rubber electrode on the back of your thigh. Several measurements will be taken while you are lying down. These measurements include a 1-millisecond stimulation. The intensity of this stimulation will vary depending on which response is being elicited. Lower intensities (50-100V) will be needed to obtain an H-reflex where higher intensities (100-200V) are needed to elicit an M-wave. The stimulations in this study feel similar to a shock of static electricity, like when you are walking across a carpet and then touch a door knob, except the voltage is much lower (A shock of static electricity can provide up to thousands of volts of electricity).

**Measure of Brain Output:**
This testing provides us important information regarding how your brain is sending messages to the muscles in your legs. You will be asked to sit in a chair, and we will position a coil over your head and adjust the position of the coil until it is in the correct spot. We will also ask you to wear a bathing cap that will have lines drawn on it to help us better locate the correct spot. A brief magnetic stimulus will then be produced which will sound like a “click.” You will not have any associated pain or discomfort in your head, but rather may feel a brief muscle twitch in the muscles of your leg or thigh. You will be asked to flex certain leg muscles at a small intensity while we provide a series of brief magnetic stimuli to your head.

**Sonographic Assessment:**
The structure of your quadriceps muscle will be assessed using a diagnostic ultrasound machine, which allows the investigators to see structures under the skin using the transmission of sound waves from a plastic probe reflected with your soft tissue. You will not feel the transmission of sound wave from the probe. During testing, an examiner will palpate your quadriceps muscle and patellar tendon, and will place the probe on your knee to take a series of images.

**Measures of Movement Patterns**
For this assessment, we want to analyze your walking. First, we will place round, reflective markers on specific landmarks on your legs. You will then be asked to walk and run on a treadmill at a self-selected pace. Cameras that are placed around the room will pick up the reflection from the markers so that we can create a digital representation of your joints while walking and/or running.

Following functional testing, your child will be asked to participate in a personal, one on one, interview regarding his/her knee injury and how it affected his/her recovery experience and
decision to return-to-sport after surgery. Interviews will be recorded with an audio recorder and a set of open-ended questions will be asked to allow for free conversation. All interviews will be transcribed verbatim at a later date to assist with data analysis.

You may be contacted at a later date in order to follow-up on responses given during the interview session. We will do this via email, if necessary.

What are the risks or inconveniences of the study?

We believe there are minimal risks associated with this research study. However, the risks are no greater than the ones you normally encounter when you participate in sports. A possible inconvenience may be the time it takes to complete the study. While the activities in this study are common to sports they may involve the following discomforts to you:

• You may experience some discomfort when the electrical shocks are applied to your skin. In order to make the shocks as comfortable as possible, large pads will be used to apply the shocks.
• You may develop transient headaches during TMS testing, although this is rare.
• Possibility of muscle strains or soreness in your lower body. Muscle soreness, following the functional testing, may be experienced in those who do not partake in daily or routine exercise that should resolve in a few days and is similar to that of beginning a new exercise regimen.
• You may experience mild skin irritation due to skin preparation and the need to remove hair from the muscle activity and ultrasound measurements sites.
• In addition, there may be uncommon or previously unknown risks that might occur. You should report any problems to the researchers.

In an effort to minimize any risk or discomfort the following has been put in place:

• Trained instructors will be present and provide feedback during all training sessions.
• You will be given the opportunity to become familiar with each exercise allowing them to perform the exercises with minimal injury risk.

The research assistants collecting this data are all Certified Athletic Trainers who are trained to minimize risks. In particular, if any task is too challenging for you, they will discontinue with that test and progress to the next task. The research assistants will monitor testing procedures as well as provide verbal instructions to ensure that you understand all testing procedures. As with any physical activity there is the potential for injury when completing functional tasks such as those included in this study. The risk of injury in this study is not considered to be greater than that of other physical activities, however, if you are not confident in your ability to jump and land on your knee, that occurs with any of the functional testing, please tell study personnel. All parts of this study are optional.

There are minimal risks associated with the interview portion of this study. We believe there are no known risks associated with this research study; however, a possible inconvenience may be the time it takes to complete the study.
What are the benefits of the study?

You may not directly benefit from this study; however, we hope that your participation in this study may benefit society and athletes with a history of knee injury specifically. Better understanding factors that affect return to sport after ACL reconstruction is important to help athletes successfully return to sport.

Will I receive payment for participation? Are there costs to participate?

There are no costs to you or your child for participating in this study other than time. We anticipate it will take your child about 10 minutes to complete the questionnaires and 90-minutes for each test session and 20 minutes for the personal interviews, plus any necessary travel time. If you participate in the longitudinal study (Aim 3) of this study, you will be compensated a total of $90 at the completion of the third and final testing session, if all three testing sessions are completed.

How will my personal information be protected?

The following procedures will be used to protect the confidentiality of your data collected. You will be assigned a random identification number that will be used on all data. This identification number will be shown on the videos instead of your name. The researchers will keep all study records (including any codes to your data) locked in a secure location. A master key that links names and identification numbers will be maintained in a separate and secure location. All participants who participate in the interview process will be identified by a pseudonym. The pseudonyms will be kept on a master list that will be in its own secure file separate from the data information. You will only be referred to by the pseudonym during transcription, data analysis and in publication. The master key, videotapes, interview information and pseudonyms will be destroyed after 3 years. All electronic files (e.g., database, spreadsheet, etc.) containing identifiable information will be password protected. Any computer hosting such files will also have password protection to prevent access by unauthorized users. Only the members of the research staff will have access to the passwords. Data that will be shared with others will be coded as described above to help protect your identity. At the conclusion of this study, the researchers may publish their findings. Information will be presented in summary format and you will not be identified in any publications or presentations. We will do our best to protect the confidentiality of the information we gather from you but we cannot guarantee 100% confidentiality.

You should also know that the UConn Institutional Review Board (IRB) and the Office of Research Compliance may inspect study records as part of its auditing program, but these reviews will only focus on the researchers and not on your responses or involvement. The IRB is a group of people who review research studies to protect the rights and welfare of research participants.

If you decide to withdraw from the study after completing one or more testing sessions, your information will be protected and secured as described above.

What happens if I am injured or sick because I took part in the study?
In the event you become sick or injured during the course of the research study, immediately notify the principal investigator or a member of the research team. If you require medical care for such sickness or injury, your care will be billed to you or to your insurance company in the same manner as your other medical needs are addressed.

However, if you believe that your illness or injury directly resulted from the research procedures of this study, you may be eligible to file a claim with the State of Connecticut Office of Claims Commissioner. For a description of this process, contact the Office of Research Compliance at the University of Connecticut at 860-486-8802.

**Can I stop being in the study and what are my rights?**

You do not have to be in this study if you do not want to. If you agree to be in the study, but later change your mind, you may drop out at any time. There are no penalties or consequences of any kind if you decide that you do not want to participate.

**Whom do I contact if I have questions about the study?**

Take as long as you like before you make a decision. We will be happy to answer any question you have about this study. If you have further questions about this study or if you have a research-related problem, you may contact the principal investigator, Lindsey Lepley at 860-486-5322 or the student researcher Julie Burland at 860-818-8266. If you have any questions concerning your rights as a research participant, you may contact the University of Connecticut Institutional Review Board (IRB) at 860-486-8802.

**Documentation of Consent:**

I have read this form and decided that I will participate in the project described above. Its general purposes, the particulars of involvement and possible risks and inconveniences have been explained to my satisfaction. I understand that I can withdraw at any time. My signature also indicates that I have received a copy of this consent form.

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<tr>
<th>Participant Signature:</th>
<th>Print Name:</th>
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<table>
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<tr>
<th>Signature of Person Obtaining Consent</th>
<th>Print Name:</th>
<th>Date:</th>
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**Permission to show video images at research conferences:**

It is sometimes beneficial for participants’ videos to be presented at a research conference. I give permission for my video to be shown during a research presentation and I understand that I will
not be identified by name. I understand that I can still participate in the research study if I do not sign below but that my video will not be shown during any presentation.

<table>
<thead>
<tr>
<th>Participant Signature:</th>
<th>Print Name:</th>
<th>Date:</th>
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**APPENDIX G**  
**Data collection forms**

**Clinical Movement Tests**

Subject Number: ___________  
Testing Date: ___________

ACL Limb: ___________  
Healthy Limb: ___________  
Dominant Limb: ___________

Single Limb Hop for Distance (SLHD)

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<th>Distance Left (cm)</th>
<th>Comments</th>
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Triple Hop (TrH)

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Clinical Movement Tests

Subject Number: ________________  Testing Date: ____________
ACL R Limb: ________________
Healthy Limb: ________________
Dominant Limb: ________________

Crossover Hop (CH)

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6-Meter Timed Hop (TiH)

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Clinical Movement Tests

Subject Number:_____________ Testing Date:__________
ACL Limb:_____________
Healthy Limb:_____________
Dominant Limb:_____________

Single  Triple  Crossover  Timed
### VICON Movement Tests

Subject Number: ____________  
ACLR Limb: ____________  
Healthy Limb: ____________  
Dominant Limb: ____________  
Testing Date: ____________

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<tr>
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<td>Right, Left or Both Limbs</td>
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<table>
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<table>
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<th>Trial Notes</th>
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<tr>
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### Physimax Movement Tests

Subject Number: ____________  
Testing Date: ____________  
ACL Limb: ____________  
Healthy Limb: ____________  
Dominant Limb: ____________  

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<th>Trial Type (Single Leg Squat; [SLsquat_X])</th>
<th>Right, Left or Both Limbs (circle)</th>
<th>Trial Notes</th>
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<tbody>
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<tr>
<td>SLsquat_03</td>
<td>Right, Left or Both Limbs</td>
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<tr>
<td>SLsquat_04</td>
<td>Right, Left or Both Limbs</td>
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<td>Right, Left or Both Limbs</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Trial Type (Double Leg Squat; [DLsquat_X])</th>
<th>Right, Left or Both Limbs (circle)</th>
<th>Trial Notes</th>
</tr>
</thead>
<tbody>
<tr>
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# Central Activation Ratio (CAR)

Subject Number: 
ACLR Limb: 
Healthy Limb: 
Dominant Limb: 

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<th></th>
<th>Right</th>
<th></th>
<th>Left</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vol.</td>
<td>Burst</td>
<td>Vol.</td>
<td>Burst</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
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</tbody>
</table>

Age: 
Height: 
Weight: 

Testing Date: 

---

184
APPENDIX H
Self-reported outcome measures

Human Performance Laboratory, ACLR Study Demographic Form

Demographic Form

Subject Number: ___________  Testing Date: ___________
Height: ___________  Weight: ___________

Instructions: Below is a list of questions about your demographics and health history. Please answer the following questions as completely as possible.

What is your sex (circle one)?
  a. male
  b. female

Date of ACL injury (if exact date is unknown, please provide an approximate date):
  a. Date: ____________________________
  b. n/a

Date of ACL surgery (if exact date is unknown, please provide an approximate date):
  a. Date: ____________________________
  b. n/a

What is your ACL injured limb?
  a. right
  b. left
  c. n/a

What ACL graft type do you have?
  c. patellar tendon (aka bone-patellar tendon bone)
  d. hamstring (aka semitendinosus gracilis)
  e. quadriceps tendon
  f. tibialis anterior
  g. other: ____________________________
  h. n/a

Was your graft type an allograft (e.g. donated tissue) or an autograft (e.g. your own tissue)?
  a. allograft (e.g. donated tissue)
  b. autograft (e.g. your own tissue)
  c. unknown
  d. n/a

Did you have any additional knee injuries besides your ACL rupture (e.g. meniscal injury, bone bruise, articular cartilage, collateral ligament damage)?
  a. yes (please describe below)
  b. no
  c. unknown
  d. n/a

yes: __________________________________________________________________________

________________________________________________________________________________

1
ACL-RSI SCALE

Instructions: Please answer the following questions referring to your main sport prior to injury. For each question tick a box ☑ between the two descriptions to indicate how you are feeling right now relative to the two extremes.

1. Are you confident that you can perform at your previous level of sport participation?

<table>
<thead>
<tr>
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<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>Fully confident</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>☐</td>
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</tbody>
</table>

2. Do you think you are likely to re-injure your knee by participating in your sport?

<table>
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<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>Not likely at all</th>
</tr>
</thead>
<tbody>
<tr>
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<td>☐</td>
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<td>☐</td>
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</tbody>
</table>

3. Are you nervous about playing your sport?

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<th>20</th>
<th>30</th>
<th>40</th>
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<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
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<th>Not nervous at all</th>
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<tr>
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</table>

4. Are you confident that your knee will not give way by playing your sport?

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<th>30</th>
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</tbody>
</table>

5. Are you confident that you could play your sport without concern for your knee?

<table>
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<th>100</th>
<th>Fully confident</th>
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6. Do you find it frustrating to have to consider your knee with respect to your sport?

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</table>
7. Are you fearful of re-injuring your knee by playing your sport?

Extremely fearful

<table>
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<th>20</th>
<th>30</th>
<th>40</th>
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No fear at all

8. Are you confident about your knee holding up under pressure?

Not at all confident

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Fully confident

9. Are you afraid of accidentally injuring your knee by playing your sport?

Extremely afraid

<table>
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Not at all afraid

10. Do thoughts of having to go through surgery and rehabilitation again prevent you from playing your sport?

All of the time

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<tr>
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<th>20</th>
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</table>

None of the time

11. Are you confident about your ability to perform well at your sport?

Not at all confident

<table>
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<tr>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
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Fully confident

12. Do you feel relaxed about playing your sport?

Not at all relaxed

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<th>20</th>
<th>30</th>
<th>40</th>
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</table>

Fully relaxed

To score: Sum individual item scores; divide by 12.
Maximum score = 100; higher score indicates more positive psychological response

IKDC Subjective Knee Evaluation

**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?
   - 4: Very strenuous activities like jumping or pivoting as in gymnastics or football
   - 3: Strenuous activities like heavy physical work, skiing or tennis
   - 2: Moderate activities like moderate physical work, running or jogging
   - 1: Light activities like walking, housework or gardening
   - 0: 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?
   - Never
   - 0
   - 1
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7
   - 8
   - 9
   - 10: Constant

3. If you have pain, how severe is it?
   - No pain
   - Never
   - 0
   - 1
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7
   - 8
   - 9
   - 10: Worst pain imaginable

4. During the **past 4 weeks**, or since your injury, how stiff or swollen has your knee been?
   - Not at all
   - 0
   - Mildly
   - 1
   - Moderately
   - 2
   - Very
   - 3
   - Extremely
   - 4

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 gymnastics or football
   - Strenuous activities like heavy physical work, skiing or tennis
   - Moderate activities like moderate physical work, running or jogging
   - Light activities like walking, housework or gardening
   - Unable to perform any of the above activities due to knee swelling

6. During the **past 4 weeks**, or since your injury, has your knee locked or caught?
   - Yes
   - 0
   - No
   - 1

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 gymnastics or football
   - Strenuous activities like heavy physical work, skiing or tennis
   - Moderate activities like moderate physical work, running or jogging
   - Light activities like walking, housework or gardening
   - Unable to perform any of the above activities due to giving way of the knee


SPORT ACTIVITIES:

8. What is the highest level of activity you can participate in on a regular basis?
   - 4 Very strenuous activities like jumping or pivoting as in gymnastics or football
   - 3 Strenuous activities like heavy physical work, skiing or tennis
   - 2 Moderate activities like moderate physical work, running or jogging
   - 1 Light activities like walking, housework or gardening
   - 0 Unable to perform any of the above activities due to knee

9. How does your knee affect your ability to:
   - Not difficult at all
   - Minimally difficult
   - Moderately difficult
   - Extremely difficult
   - Unable to do

   a. Go up stairs
   b. Go down stairs
   c. Kneel on the front of your knee
   d. Squat
   e. Sit with your knee bent
   f. Rise from a chair
   g. Run straight ahead
   h. Jump and land on your involved leg
   i. Stop and start quickly

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 sport?

FUNCTION PRIOR TO YOUR KNEE INJURY:

<table>
<thead>
<tr>
<th>Couldnt perform daily activities</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>No limitation in daily activities</th>
</tr>
</thead>
</table>

CURRENT FUNCTION OF YOUR KNEE:

<table>
<thead>
<tr>
<th>Cannot perform daily activities</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>No limitation in daily activities</th>
</tr>
</thead>
</table>
KOOS KNEE SURVEY

Today’s date: _____/_____/______ Date of birth: _____/_____/______

Name: ____________________________________________________

INSTRUCTIONS: This survey asks for your view about your knee. This information will help us keep track of how you feel about your knee and how well you are able to perform your usual activities. Answer every question by ticking the appropriate box, only one box for each question. If you are unsure about how to answer a question, please give the best answer you can.

Symptoms
These questions should be answered thinking of your knee symptoms during the last week.

S1. Do you have swelling in your knee?
   - Never
   - Rarely
   - Sometimes
   - Often
   - Always

S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?
   - Never
   - Rarely
   - Sometimes
   - Often
   - Always

S3. Does your knee catch or hang up when moving?
   - Never
   - Rarely
   - Sometimes
   - Often
   - Always

S4. Can you straighten your knee fully?
   - Always
   - Often
   - Sometimes
   - Rarely
   - Never

S5. Can you bend your knee fully?
   - Always
   - Often
   - Sometimes
   - Rarely
   - Never

Stiffness
The following questions concern the amount of joint stiffness you have experienced during the last week in your knee. Stiffness is a sensation of restriction or slowness in the ease with which you move your knee joint.

S6. How severe is your knee joint stiffness after first wakening in the morning?
   - None
   - Mild
   - Moderate
   - Severe
   - Extreme

S7. How severe is your knee stiffness after sitting, lying or resting later in the day?
   - None
   - Mild
   - Moderate
   - Severe
   - Extreme
**Pain**

P1. How often do you experience knee pain?

<table>
<thead>
<tr>
<th></th>
<th>Never</th>
<th>Monthly</th>
<th>Weekly</th>
<th>Daily</th>
<th>Always</th>
</tr>
</thead>
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</tbody>
</table>

What amount of knee pain have you experienced the **last week** during the following activities?

P2. Twisting/pivoting on your knee

<table>
<thead>
<tr>
<th></th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
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</table>

P3. Straightening knee fully

<table>
<thead>
<tr>
<th></th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
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P4. Bending knee fully

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<thead>
<tr>
<th></th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
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P5. Walking on flat surface

<table>
<thead>
<tr>
<th></th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
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</table>

P6. Going up or down stairs

<table>
<thead>
<tr>
<th></th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
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<tbody>
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</table>

P7. At night while in bed

<table>
<thead>
<tr>
<th></th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
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</table>

P8. Sitting or lying

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<thead>
<tr>
<th></th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
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</table>

P9. Standing upright

<table>
<thead>
<tr>
<th></th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
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</table>

**Function, daily living**

The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A1. Descending stairs

<table>
<thead>
<tr>
<th></th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
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</thead>
<tbody>
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</table>

A2. Ascending stairs

<table>
<thead>
<tr>
<th></th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
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</tbody>
</table>
For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

<table>
<thead>
<tr>
<th>Activity</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3. Rising from sitting</td>
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<tr>
<td>A4. Standing</td>
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<tr>
<td>A5. Bending to floor/pick up an object</td>
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<tr>
<td>A6. Walking on flat surface</td>
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<tr>
<td>A7. Getting in/out of car</td>
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<td>A8. Going shopping</td>
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<tr>
<td>A9. Putting on socks/stockings</td>
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<td>A10. Rising from bed</td>
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<tr>
<td>A11. Taking off socks/stockings</td>
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<tr>
<td>A12. Lying in bed (turning over, maintaining knee position)</td>
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<tr>
<td>A13. Getting in/out of bath</td>
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<td>A14. Sitting</td>
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<td>A15. Getting on/off toilet</td>
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</table>
For each of the following activities please indicate the degree of difficulty you have experienced in the last week due to your knee.

| A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc) |
|---|---|---|---|---|---|
| None | Mild | Moderate | Severe | Extreme |
| | | | | |

| A17. Light domestic duties (cooking, dusting, etc) |
|---|---|---|---|---|
| None | Mild | Moderate | Severe | Extreme |
| | | | | |

**Function, sports and recreational activities**
The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the last week due to your knee.

| SP1. Squatting |
|---|---|---|---|---|
| None | Mild | Moderate | Severe | Extreme |
| | | | | |

| SP2. Running |
|---|---|---|---|---|
| None | Mild | Moderate | Severe | Extreme |
| | | | | |

| SP3. Jumping |
|---|---|---|---|---|
| None | Mild | Moderate | Severe | Extreme |
| | | | | |

| SP4. Twisting/pivoting on your injured knee |
|---|---|---|---|---|
| None | Mild | Moderate | Severe | Extreme |
| | | | | |

| SP5. Kneeling |
|---|---|---|---|---|
| None | Mild | Moderate | Severe | Extreme |
| | | | | |

**Quality of Life**

| Q1. How often are you aware of your knee problem? |
|---|---|---|---|---|
| Never | Monthly | Weekly | Daily | Constantly |
| | | | | |

| Q2. Have you modified your life style to avoid potentially damaging activities to your knee? |
|---|---|---|---|---|
| Not at all | Mildly | Moderately | Severely | Totally |
| | | | | |

| Q3. How much are you troubled with lack of confidence in your knee? |
|---|---|---|---|---|
| Not at all | Mildly | Moderately | Severely | Extremely |
| | | | | |

| Q4. In general, how much difficulty do you have with your knee? |
|---|---|---|---|---|
| None | Mild | Moderate | Severe | Extreme |
| | | | | |

*Thank you very much for completing all the questions in this questionnaire.*
TEGNER ACTIVITY LEVEL SCALE

Please indicate in the spaces below the HIGHEST level of activity that you participated in BEFORE YOUR INJURY and the highest level you are able to participate in CURRENTLY.

BEFORE INJURY:  Level__________          CURRENT:     Level___________

<table>
<thead>
<tr>
<th>Level</th>
<th>Activity</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>Level 6</td>
<td>Recreational sports- soccer, football, rugby, bandy, ice hockey, basketball, squash, racquetball, running</td>
</tr>
<tr>
<td>Level 5</td>
<td>Competitive sports- tennis and badminton, handball, racquetball, down-hill skiing, jogging at least 5 times per week</td>
</tr>
<tr>
<td>Level 4</td>
<td>Work- heavy labor (construction, etc.)</td>
</tr>
<tr>
<td>Level 3</td>
<td>Work- moderately heavy labor (e.g. truck driving, etc.)</td>
</tr>
<tr>
<td>Level 2</td>
<td>Work- light labor</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>

The Knee Self-Efficacy Scale (K-SES)
Please grade the following questions on the scale from 0-10.
0 = not at all, 10 = very certain

A. Daily Activities
How certain are you about:
1. Walking in the forest
2. Climbing up and down a hill/stairs
3. Going out dancing
4. Jumping ashore from a boat
5. Running after small children
6. Running for the tram/bus
7. Working in the garden

B. Sports and Leisure activities
How certain are you about:
1. Cycling a long distance
2. Cross country skiing
3. Riding a horse
4. Swimming
5. Hiking in the mountains

C. Physical Activities
How certain are you about:
1. Squatting
2. Jumping sideways from one leg to the other
3. Working out hard a short time after the injury or surgery
4. Doing one-leg hops on the injured leg
5. Moving around in a rocking small boat
6. Doing fast twisting

D. Your knee function in the future
1. How certain are you that you can return to the same physical activity level as before the injury?
2. How certain are you that you would not suffer any new injuries to your knee?
3. How certain are you that your knee will not “break”?
4. How certain are you that your knee will not get worse than before surgery?
**Tampa Scale for Kinesiophobia**  
*(Miller, Kori and Todd 1991)*

1 = strongly disagree  
2 = disagree  
3 = agree  
4 = strongly agree

<p>| | | | | | | | | | |</p>
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</tr>
</thead>
<tbody>
<tr>
<td>1. I’m afraid that I might injury myself if I exercise</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2. If I were to try to overcome it, my pain would increase</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td></td>
<td></td>
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<tr>
<td>3. My body is telling me I have something dangerously wrong</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td></td>
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<tr>
<td>4. My pain would probably be relieved if I were to exercise</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td></td>
<td></td>
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<tr>
<td>5. People aren’t taking my medical condition seriously enough</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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<tr>
<td>6. My accident has put my body at risk for the rest of my life</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td></td>
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</tr>
<tr>
<td>7. Pain always means I have injured my body</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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<td></td>
<td></td>
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<tr>
<td>8. Just because something aggravates my pain does not mean it is dangerous</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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<td></td>
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</tr>
<tr>
<td>9. I am afraid that I might injure myself accidentally</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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<td>10. Simply being careful that I do not make any unnecessary movements is the safest thing I can do to prevent my pain from worsening</td>
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<td>11. I wouldn’t have this much pain if there weren’t something potentially dangerous going on in my body</td>
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<td>12. Although my condition is painful, I would be better off if I were physically active</td>
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<td>13. Pain lets me know when to stop exercising so that I don’t injure myself</td>
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<td>14. It’s really not safe for a person with a condition like mine to be physically active</td>
<td>1</td>
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<td>15. I can’t do all the things normal people do because it’s too easy for me to get injured</td>
<td>1</td>
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<td>16. Even though something is causing me a lot of pain, I don’t think it’s actually dangerous</td>
<td>1</td>
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<tr>
<td>17. No one should have to exercise when he/she is in pain</td>
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THE VETERANS RAND 12-ITEM HEALTH SURVEY (VR-12)

The following questions ask for your views about your health—how you feel and how well you are able to do your usual activities. All kinds of people across the country are being asked these same questions. Their answers and yours will help to improve health care for everyone. There are no right or wrong answers; please choose the answer that best fits your life right now.

Answer each question by marking an ‘X’ next to the best response. For example:

What is your gender?
☐ Male
☐ Female

Q1. In general, would you say your health is:
☐ Excellent
☐ Very good
☐ Good
☐ Fair
☐ Poor

Q2. The following questions are about activities you might do during a typical day. Does your health now limit you in these activities? If so, how much?

a. Moderate activities, such as moving a table, pushing a vacuum cleaner, bowling or playing golf?
☐ Yes, limited a lot
☐ Yes, limited a little
☐ No, not limited at all

b. Climbing several flights of stairs?
☐ Yes, limited a lot
☐ Yes, limited a little
☐ No, not limited at all
Q3. During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of your physical health?

a. Accomplished less than you would like.
   - No, none of the time
   - Yes, a little of the time
   - Yes, some of the time
   - Yes, most of the time
   - Yes, all of the time

b. Were limited in the kind of work or other activities.
   - No, none of the time
   - Yes, a little of the time
   - Yes, some of the time
   - Yes, most of the time
   - Yes, all of the time

Q4. During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of any emotional problems (such as feeling depressed or anxious)?

a. Accomplished less than you would like.
   - No, none of the time
   - Yes, a little of the time
   - Yes, some of the time
   - Yes, most of the time
   - Yes, all of the time

b. Didn’t do work or other activities as carefully as usual.
   - No, none of the time
   - Yes, a little of the time
   - Yes, some of the time
   - Yes, most of the time
   - Yes, all of the time

Continue to next page
Q5. During the past 4 weeks, how much did pain interfere with your normal work (including both work outside the home and housework)?

- Not at all
- A little bit
- Moderately
- Quite a bit
- Extremely

These questions are about how you feel and how things have been with you during the past 4 weeks. For each question, please give the one answer that comes closest to the way you have been feeling.

Q6a. How much of the time during the past 4 weeks: Have you felt calm and peaceful?

- All of the time
- Most of the time
- A good bit of the time
- Some of the time
- A little of the time
- None of the time

Q6b. How much of the time during the past 4 weeks: Did you have a lot of energy?

- All of the time
- Most of the time
- A good bit of the time
- Some of the time
- A little of the time
- None of the time

Q6c. How much of the time during the past 4 weeks: Have you felt downhearted and blue?

- All of the time
- Most of the time
- A good bit of the time
- Some of the time
- A little of the time
- None of the time

Continue to next page
Q7. During the past 4 weeks, how much of the time has your physical health or emotional problems interfered with your social activities (like visiting with friends, relatives, etc.)?

- All of the time
- Most of the time
- Some of the time
- A little of the time
- None of the time

Now, we’d like to ask you some questions about how your health may have changed.

Q8. Compared to one year ago, how would you rate your physical health in general now?

- Much better
- Slightly better
- About the same
- Slightly worse
- Much worse

Q9. Compared to one year ago, how would you rate your emotional problems (such as feeling anxious, depressed or irritable) now?

- Much better
- Slightly better
- About the same
- Slightly worse
- Much worse

Your answers are important!

Thank you for completing this questionnaire!
Single Assessment Numeric Evaluation

How would you rate your knee’s function, with 100 being normal?

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REFERENCES


