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# Drop Vertical Jump Landing Biomechanics Following Anterior Cruciate Ligament Reconstruction With and Without Lateral Extra-Articular Tenodesis

Lindsey O'Neill, *The University of Western Ontario*

Supervisor: Trevor Birmingham, *The University of Western Ontario*

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# Abstract

The lateral extra-articular tenodesis (LET) performed with anterior cruciate ligament (ACL) reconstruction is intended to add stability to the knee, yet the procedure may compromise lateral knee soft tissues that may affect performance during functionally demanding activities. This study compared knee landing biomechanics during a Drop Vertical Jump (DVJ) performed by 154 patients randomized to ACL reconstruction alone or ACL reconstruction plus LET. Three-dimensional knee moments and angles during the DVJ were investigated at 6 and 12 months postoperative. The peak knee abduction moment (KAM) was the primary outcome measure. There were no statistically significant differences between groups in any of the landing biomechanics assessed. The mean difference (95% confidence interval) in the peak KAM between groups was -4.15 Nm (-10.36 – 2.05) at 6 month and 1.92 Nm (-4.77 – 5.89) at 12 months for patients that completed testing at both follow-ups. The present findings suggest the LET does not benefit or hinder landing biomechanics.



# Keywords

Anterior cruciate ligament, anterior cruciate ligament reconstruction, lateral extra-articular tenodesis, drop vertical jump, knee abduction moment

## Co-Authorship Statement

This project included a subsample from a larger ongoing multi-centered randomized clinical trial led by Dr. Alan Getgood and Dr. Dianne Bryant. My roles were data collection, analysis and writing of this thesis under the supervision of Dr. Trevor Birmingham.

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# List of Abbreviations

| | |
|---|---|
| ACL | Anterior cruciate ligament |
| PCL | Posterior cruciate ligament |
| MCL | Medial collateral ligament |
| LCL | Lateral collateral ligament |
| LET | Lateral extra-articular tenodesis |
| ALL | Anterolateral ligament |
| DVJ | Drop vertical jump |
| KAM | Knee abduction moment |
| KAA | Knee abduction angle |
| KFM | Knee flexion moment |
| KFA | Knee flexion angle |
| KIRM | Knee internal rotation moment |
| KIRA | Knee internal rotation angle |
| VGRF | Vertical ground reaction force |
| IT | Iliotibial |
| ACLR | Anterior cruciate ligament reconstruction |
| WOBL | Wolf Orthopaedic Biomechanics Lab |
| FKSMC | Fowler Kennedy Sport Medicine Clinic |
| IA | Intra-articular |
| EA | Extra-articular |
| BPTB | Bone-patellar tendon bone |
| HT | Hamstring tendon |
| KOOS | Knee Injury and Osteoarthritis Outcomes Scores |

# Chapter 1

## 1 Introduction

The anterior cruciate ligament (ACL) is one of four main ligaments in the knee and provides about 85% of the restraining force to anterior tibial displacement at 30 degrees and 90 degrees of knee flexion.[1] The purpose of ACL reconstruction (ACLR) surgery is to restore functional stability to the knee following a complete or partial tear. However, recent studies have shown high rates of graft failure and anterolateral instability among standard ACLR procedures[2]. Consequently, there is an increasing interest in combining ACLR with extra-articular augmentation. [3, 4, 5, 6] In particular, the lateral extra-articular tenodesis (LET), which is comprised of a portion of the iliotibial (IT) band, may be able to provide additional stability and restore normal knee biomechanics in comparison to standard ACL surgery, which in turn may reduce the risk of future ACL injuries.

The LET procedure has yielded promising results that suggest it may protect the ACL graft from excessive loads and improve anterolateral rotational control.[7] Alternatively, other studies suggest that the LET procedure may reduce functional stability because it compromises the lateral musculature and soft tissue restraints at the knee.[3, 8] Specifically, the IT band provides restraint against internal rotation and anterior translation of the tibia, and its integrity may be compromised at the expense of constructing the LET.[6, 9, 10, 11] Importantly, there is currently little known about the effect that ACLR combined with LET has on the knee during functionally demanding activities.

The drop vertical jump (DVJ) has proven to be an important test of lower limb function in participants at risk of ACL injury.[12-19] Knee valgus collapse is one of the most important factors screened for in jump-landing performance for ACL injury risk.[51] Knee valgus collapse may be indicative of a ligament dominant landing technique that is characterized by the use of bony configuration, articular cartilage and ligaments to absorb large forces during activity rather than using the prime muscle movers of the lower extremities.[14] This produces large moments about the knee with increased anterior tibial translation, resulting in a large load on the ACL.[13, 22, 51] In particular, the knee abduction moment (KAM) measured during the DVJ associated with greater valgus collapse, anterior tibial translation and risk of ACL tear.[12, 13, 20-22] While it is plausible that the LET may benefit or hinder landing biomechanics during a DVJ, this has not been previously investigated.

## 1.1 Objectives and Hypothesis

The objective of the present study was to compare landing biomechanics during a DVJ between patients who underwent ACLR alone and patients who underwent ACLR combined with LET. The primary outcome measure was the peak KAM during the DVJ. We hypothesized that the peak KAM would be statistically different between those who get ACLR alone and those who get ACLR plus the LET.

# Chapter 2

# 2 Literature Review

This chapter will provide an overview of the anatomy of the knee joint with the main focus being the ACL and its reconstructive techniques used, especially extra-articular augmentation. The chapter will also provide an overview of knee landing biomechanics during a drop vertical jump (DVJ) assessed using a movement analysis laboratory.

## 2.1 Anatomy of the Knee

The knee is a large and complex joint.[21] It is a modified hinge joint that allows for flexion and extension, as well as slight medial and lateral rotation in a flexed position. It contains a single synovial cavity consisting of three joints including two tibiofemoral joints, made up of the tibial plateau and the lateral and medial condyles of the femur, as well as the patellofemoral joint between the posterior aspect of the patella and the anterior surface of the femur.[21]

The quadricep and hamstring muscles are key dynamic stabilizers of the knee. The quadriceps are the extensors of the knee and they include rectus femoris, vastus medialis, vastus lateralis, and vastus intermedius. They act as springs and shock absorbers, decreasing the force from high impact loading during running and jumping.[23] Hamstrings are the flexors of the knee and they include biceps femoris, semitendinosus, and semimembranosus. They act as antagonistic muscles preventing the leg from going into hyperextension as a result of large forces produced by the quadriceps.[23] The popliteus muscle is also an important knee stabilizer strengthening the lateral part of the posterior surface of the joint.[21]

The passive stabilizers of the knee include both extracapsular and intracapsular structures. There are five extracapsular structures that strengthen the capsule itself, including the patellar ligament, oblique popliteal ligament, arcuate popliteal ligament, tibial/medial collateral ligament (MCL), and fibular/lateral collateral ligament (LCL) (9). The MCL and LCL tend to be the most commonly injured extracapsular structures.

The MCL is a broad flat ligament that runs along the medial surface of the knee joint, and extends from the medial condyle of the femur to the medial condyle of the tibia.[21] Edward et al.[24] conducted a study where the MCL was removed and results showed greater medial joint space opening when a force was applied to the lateral aspect of knee at 5 and 25 degrees of flexion. The MCL also acts as secondary restraint providing resistance against external rotation of the tibia[25], as well as anterior or posterior translation of the tibia.[23, 26]

The LCL is a strong cord like ligament that runs along the lateral surface of the knee extending from the lateral condyle of the femur to the lateral side of the head of the fibula.[21, 23] The LCL is thought to be the primary restraint during varus stress, preventing lateral joint opening[24], and a secondary restraint during internal rotation of the tibia[25], as well as anterior or posterior translation of the tibia.[23, 26]

In addition to the external structures that support the knee, there are also three main structures within the knee capsule that act as important stabilizers. These include the menisci (lateral and medial), the posterior cruciate ligament (PCL), and the anterior cruciate ligament (ACL).

The menisci are crescent-shaped fibrocartilage discs that sit between the tibial and femoral condyles.[21] The primary functions of these discs are to reduce friction within the knee joint by providing lubrication, and to circulate the synovial fluid within the joint.[21,23] To some degree they may also have a secondary role as shock absorbers.[21]

The PCL is slightly larger than the ACL and is made up of two bundles.[23] It extends anteriorly and medially from the posterior intercondylar area of the tibia and lateral meniscus to the lateral aspect of the anterior surface of the medial condyle of the femur.[21, 23] It plays an important role in the resistance of anterior-posterior shear forces acting on the knee whereby limiting the amount of anterior translation of the femur on the tibia.[21, 23] Injuries to the PCL are less common than they are to the ACL, accounting for only 5-20% of all injuries to the knee.[23]

### 2.1.1 Anterior Cruciate Ligament

The ACL extends posteriorly and laterally from an impression just anterior to the intercondylar area of the tibial plateau inserting into the posterior part of the medial surface of the lateral condyle of the femur. The ACL is composed of two bundles, the anteromedial bundle and the posterolateral bundle.[5] Some fibres that make up the ligament will remain taut throughout the full range of motion; however, the majority of them, especially the ones of the posterolateral bundle, become more taut as the knee reaches full extension.[23] On average the twisted collagen fibres of the ACL form a structure that runs about 38mm in length and 11mm in width.[4] Many authors have concluded that the ACL is the primary restraint of anterior translation of the tibia on the femur,[4, 5, 12, 20, 21, 23, 26, 27] accounting for about 85% of the resistance during this movement.[23] The ACL has also been shown to play a secondary restraining role with medial and lateral joint opening, as well as internal and external rotation of the tibia.[24, 28, 29] In addition to providing mechanical stability, the ACL also contains a significant number of mechanoreceptors that play an important role in proprioception. Proprioception is a sensory modality that allows an individual to sense and control joint position and movement.[54] These mechanoreceptors are important for detecting change in tension, speed, acceleration, direction of movement, and the position of the knee.[54]

### 2.1.2 Anterolateral Ligament

The anterolateral ligament (ALL) is less commonly described, and is sometimes confused as a continuation of the iliotibial band.[30] Some have reported the existence of a lateral capsulo-ligamentous structure connecting the femur with the tibia, but its true anatomy had not been understood until recent studies were conducted to investigate the anatomy of the structure. Claes et al. dissected 41 knees and found in all but one a distinct ligamentous structure on the anterolateral aspect of the knee joint.[9] Results showed that the major origin of the ALL was the prominence of the lateral femoral condyle, just anterior to the origin of the LCL.[9] They also found that some of the fibres extended towards the lateral intermuscular septum and others blended with the proximal portion of the LCL.[9] With the body of the structure running obliquely, it connects to the anterolateral side of the proximal tibia just posterior to Gerdy's tubercle, with a strong connection above and under the rim of the lateral meniscus.[9] In 2015, Kennedy et al.[31] found that in all specimens the ALL structure came under tension during a combined 30 degrees of knee flexion and internal rotation. Two years earlier, Claes et al.[9] also concluded that the ALL came under maximal tension during combined flexion and internal rotation of the tibia. Segond fracture, which is an avulsion fracture of the ALL at its distal insertion on the tibia, is often associated with ACL tears.[9, 30, 31] This has led to the suggestion that standard ACLR may leave some degree of rotational instability, and that an extra-articular augmentation may be beneficial.[3, 31]

## 2.2 Iliotibial Band

The iliotibial (IT) band is a large complex structure divided into different layers with multiple attachment sites. Vieira et al.[10] described the anatomy of the IT band. It has three layers – the superficial layer, the deep layer, and the capsulo-osseous layer. Its main attachments include: insertion at the linea aspera, insertion at the upper edge of the lateral epicondyle, patellar insertion on the lateral retinaculum forming part of the lateral patellofemoral ligament, and a wide insertion at and around Gerdy's tubercle.[10] Of the three layers, the most well defined ligamentous structure is the capsular-osseous layer which some refer to as the anterolateral ligament. However, Claes et al.[9] found there to be no connection between this layer, or any layer of the IT band, with the ALL and should therefore be considered separate structures.[9] The IT band, especially the capsular-osseous layer, plays an important role as both a static and dynamic stabilizer of the knee joint. Terry et al.[11] studied 82 knees with acute knee injuries that were ACL deficient and found that with injury to the capsular osseous-layer there was greater pivot shift, lateral joint space opening, and anterior tibial translation and 90 degrees of flexion. Vieira et al.[10] found similar results during their anatomical study of the IT band, concluding that the capsular-osseous layer prevented anterolateral subluxation of the tibia, and restricted anterior tibial translation.

## 2.3 Anterior Cruciate Ligament Injury

Trauma to the ACL is a common sport injuries with ACLR being the sixth most common orthopaedic procedure performed, costing over half a billion dollars each year.[3] The aim of ACLR is to re-establish functional stability of the knee and allow patients to return to the level of activity they were at before the injury. However, due to the lack of rotational stability following surgery and a high rate of re-injury some patients are unable to do so.[3, 32] Webster et al.[32] followed 354 patients after ACL surgery, and of those patients 18% experienced graft failure and 17.7% suffered a contralateral ACL tear.

According to Lind et al.[2] revision of the ACL is most frequently seen 1-2 years after the initial reconstruction, especially for patients below the age of 20 years old. They also found that the patients' Knee Injury and Osteoarthritis Outcome Scores (KOOS) were worse following revision compared to primary ACLR.

An ACL tear can be a season-ending and devastating injury, especially to those individuals who compete in sport at high levels. Females are at a higher risk of injury between the ages of 14 to 18 years, while males tend to be at a higher risk between the ages of 19 to 25.[33] In a study conducted by Sanders et al.[33] they followed ACLR patients over a 20-year period and found that male patients had a significantly higher annual incidence rate compared to females, but they attributed these results to the fact that more males participate in competitive, high-energy sports. Despite males accounting for a larger portion of annual ACL tears, females are actually four to six times more likely to tear their ACL compared to males when participating in jumping and cutting activities.[12,34]

When looking at the mechanism of injury of an ACL tear it can occur through either a contact or non-contact situation, but studies have shown that the majority of these injuries are the result of non-contact movements.[3, 20] Contact injuries are usually the result of force applied to the lateral aspect of the leg or knee resulting in a greater valgus movement at the knee.[20] In the case of non-contact ACL tears, the common mechanism of injury is a sudden deceleration on an almost fully extended single-leg maneuver followed by a change in direction.[20] Individuals that participate in soccer, basketball, or football seem to account for the majority of sport-related ACL injuries.[3, 12, 20, 33, 34]

## 2.4 Surgical Reconstruction

Individuals can either choose to manage their ACL injury by seeking surgical or non-surgical interventions. The decision may depend on a number of factors including, but limited to, the degree of functional knee stability, activity level desired, occupation, and age.[35] Conservative, non-surgical interventions typically consist of physical therapy, bracing and activity modification.[35] Surgical intervention is often recommended for individuals participating in jumping or cutting sports, or have demanding jobs.[35] This section will focus on ACLR and intra-articular graft options, as well as extra-articular reconstruction.

### 2.4.1 Intra-articular Graft Selection

Several authors have described different aspects of ACLR with the goal of refining the procedure to produce a "gold standard".[36] Such topics include tunnel placement, use of single- or double-bundle technique, types of fixation, and graft selection.[36]

Graft selection in ACLR is a common topic of discussion. There are three main types of grafts: (1) allograft – cadaveric tissue donated from another human, (2) autograft – tissue harvested from the patient, but taken from a different area of the body, and (3) synthetic graft – constructed from biomaterials such as carbon fibre and polyethylene to name a few.[36] The use of synthetic grafts has been attributed to high rates of complications and so there has been more of a focus on allografts and autografts.[36]

In 2013, Kraeutler et al.[37] conducted a meta-analysis that included 76 studies investigating 5182 patients between 1996 and 2012 who underwent ACLR using either an allograft bone-patellar tendon –bone (BPTB) or autograft BPTB. Their results showed that patients with the allograft had a 3-fold increase in re-rupture rate compared with the autograft (12.7% vs. 4.3%).[37] In 2014, these results were further supported by Bottoni et al.[38] who found that allograft failure (26.5%) was three times higher than autograph failure (8.3%) in 97 knees after a minimum 10 year follow-up.

Autografts and allografts can be taken from different locations within the body.[36] Autografts harvested from the patient can be taken from BPTB, hamstrings, quadriceps tendon, or fascia lata.[36] Allografts from cadavers can be taken from BPTB, hamstrings, quadriceps tendon, tibialis anterior, achilles tendon, or fascia lata.[36] Both autografts and allografts have their advantages. Some of the advantages that have been associated with autografts include lower graft failure rate, lower infection rate, and lower cost.[36] Allografts on the other hand are said to lead to faster post-operative recovery, less post-operative pain, and there are a variety of graft sizes available.[36] A major concern with the use of allografts is the transmission of infectious diseases. In 2010, Greenberg et al.[39] compared the infection rate for primary ACLR between patients who received autografts and those who received allografts and found that there was no significant increase in risk of clinical infection with the use of allografts.

Of the grafts available for ACLR the most popular one seems to be autografts. From the autografts listed above the most highly researched and controversial discussions revolve around whether the BPTB graft or the hamstring tendon (HT) graft is better.[4] Freedman et al.[40] conducted a meta-analysis comparing 1348 BPTB graft patients from 21 studies to 628 HT graft patients in 13 studies. They concluded that graft failure was significantly lower amongst BPTB graft patients (1.9%) compared to HT graft patients (4.9%); however, those patients with BPTB graft experienced greater complication rates including increased anterior knee pain.[40] When considering the results from this study it is important to take into consideration that the BPTB group had more than double the number of patients than the HT group.

In 2011, Mohtadi et al.[41] did a review of the literature comparing BPTB autograft to HT autograft. They found that there was no statistically significant difference between the groups in re-rupture rate, but similar to Freedman et al., they found that BPTB patients had a higher incidence of pain and discomfort on the anterior aspect of the knee.

### 2.4.2 Extra-Articular Reconstruction

The idea of using extra-articular reconstruction in conjunction with ACLR is not new. It was first attempted by Fritz Lang in 1903 when he constructed a prosthetic ligament made of silk, and placed it extra-articularly in the hope that it would help stabilize an ACL deficient knee.[6] Sustaining an ACL injury can lead to injury of anterolateral structures of the knee which may be a contributing factor as to why some patients still experience joint instability following ACLR, and in turn leads to re-injury of the ACL.[3, 4, 5, 9, 27, 30, 31, 42-45] In an attempt to combat this instability there has been a growing interest in using extra-articular reconstruction in addition to the traditional ACLR by using what has been called the lateral extra-articular tenodesis (LET). Commonly, the LET is constructed by cutting away a strip of the IT band, with its distal attachment on Gerdy's tubercle remaining intact, and the free end being fixated to the femur just proximal to the femoral insertion of the LCL.[3, 4, 5, 43] However, some LET structures have been constructed using the biceps femoris tendon.[5] Potential benefits of using the LET are presently unclear. Getgood et al.[3] conducted a study where patients were randomized to either ACLR alone or ACLR plus LET. They found that at the 6 month and 12 month follow-up periods patients from the ACLR plus LET group had significantly lower quadricep strength, which was believed to be attributed to the LET procedure.[3]

In 1993, Amis et al.[8] used cadaveric knees in an Instron machine to compare anterior tibial translation and tibial rotation between intact knees, ACL ruptured knees, intra-articular (IA) reconstructed knees, IA plus extra-articular (EA) reconstructed knees, and ACL deficient with EA reconstruction only knees. Their results suggested that the IA plus EA reconstructed knees did not provide any additional support with anterior translation or rotational stability of the tibia compared to intact knees and IA reconstructed knees.[8] In addition, they found that the ACL deficient with EA reconstruction only knees did give significantly greater anterior stability than ACL ruptured knees, but significantly less stability than the intact knees.[8]

Despite Amis' results, more recent studies have highlighted the potential benefits of using extra-articular reconstruction. In 2016, Inderhaug et al.[27] investigated 12 cadaveric knees and compared anterior tibial translation and internal rotation following anterolateral procedures combined with ACLR. Their results showed that ACLR alone was not able to restore normal knee biomechanics, specifically with anterior translation and internal rotation, following an injury to both the ACL and the ALL.[27] However they did conclude that the use of the tenodesis tensioned with 20N and combined with ACLR was successful in restoring native knee laxity and biomechanics.[27]

In 2015, Hewison et al. conducted a systematic review to determine if the addition of the LET to standard ACLR would provide greater control of rotational laxity and improved clinical outcomes compared to ACLR alone. Of the 106 studies that were selected for full-text review, 29 met the inclusion criteria. The meta-analysis concluded that there was a statistically significant reduction in pivot shift with the combined procedure compared to the ACL alone procedure. However, it is important to note that some of the studies lacked sufficient internal validity, sample size, consistent methodology, and standardized protocols.[53]

## 2.5 Predictive Risk Factors for ACL Injury

There are a number of predictive risk factors for ACL tear that have been well documented, some of which are considered modifiable risks while others are not. The most common nonmodifiable risk factors include anatomical and hormonal factors, and the studied modifiable risk factor is neuromuscular control.[13, 46, 47]

One of the anatomical risk factors is the width of the intercondylar notch, and some studies have found a correlation between ACL size and notch-width index. Authors concluded that a smaller notch lead to smaller ACL volume, which in turn leads to a greater risk of ACL tears.[46, 47] Another risk factor is generalized joint and ligamentous laxity. When measuring anterior-posterior joint laxity studies have identified hyperextension and laxity side-to-side differences as significant risk factors in both males and females for ACL tear, especially in non-contact situations.[46, 47] Another important anatomical risk is the slope of the tibial plateau. The geometry of the tibiofemoral joint plays an important role in controlling and dispersing large compression and shear forces across the knee.[47] Individuals who sustain ACL injuries have a significantly increased lateral tibial slope, and a shallower medial tibial slope, which puts a large amount of strain on the ACL exceeding its failure strength and leading to injury.[46]

Hormones are often considered a nonmodifiable risk factor for ACL injury that affects women more so than men.[13, 46] The fibroblasts that make up the ACL have estrogen receptors, and estrogen contributes to the tensile properties of ligaments.[46] Research has shown that females are more prone to ACL injury during the preovulatory stage of the menstrual cycle. The use of oral contraceptive pills has been suggested as a method to help control hormonal imbalance and improve dynamic and passive stability of the knee.[46]

Perhaps the most talked about modifiable risk factor, neuromuscular imbalance, can be divided into four categories: ligament dominance, quadricep dominance, leg dominance, and trunk dominance.[14] Ligament dominance has been defined as neuromuscular imbalance leading to valgus collapse, which is seen more often in women than men.[14, 46] Improper recruitment of lower extremity muscles, and lateral movement of the trunk can force the knee into a valgus position increasing the load on the ACL.[14, 46] In 2005, Hewett et al.[13] used three-dimensional (3D) movement analysis during a jump landing maneuver to screen 205 female athletes prior to the start of their seasons. Nine of these athletes suffered an ACL injury. These nine individuals had significantly different knee posture than the other 196 individuals including greater knee abduction angles at landing, a 2.5 greater KAM, and a 20% higher ground reaction force.[13] These results suggest that the nine individuals had higher ligament dominance than the patients who did not sustain an ACL injury.

Quadricep dominance is also a concept that is seen more with females than males, as females tend to land from a jump with less knee flexion.[14] When contracting the quadriceps with a large amount of force, and not using the posterior chain muscles to counteract that force, the leg ends up in more of an extended position putting more stress on the ACL, and this is a common mechanism seen with ACL injuries.[14] In 2016, Leppänen et al.[15] analyzed peak knee abduction moment, peak knee flexion angle, and peak vertical ground reaction force of basketball and floorball players during a DVJ. They found that lower peak knee flexion angles and higher vertical ground reaction forces were associated with increased risk of ACL injury.[15] These results lead the authors to conclude that stiff landings, with greater extension angles, were associated with increased ACL injury risk.

There is little evidence to support leg dominance as a risk factor for ACL injury. However, the theory behind it is that individuals may experience side-to-side asymmetry in terms of muscle recruitment, muscle strength, and muscle flexibility, which may increase their risk of an ACL injury.[14, 46] An individual is considered leg dominant when muscular asymmetry is measurable.[14]

The idea of trunk dominance has been defined as not being able to control the movement of the trunk following a perturbation, or having a sense of trunk position in three-dimensional space.[14] In 2007, Zazulak et al.[48] studied the deficits in neuromuscular control of the trunk as a predictor of knee injuries. They investigated 277 collegiate athletes and found that trunk displacement, specifically lateral displacement, was greater in athletes with knee, ligament, and ACL injuries compared to the uninjured athletes, but these results only applied to the female athletes.[48] For the male athletes, the only significant predictor for ACL injury was a history of low back pain. There has been little evidence to show that trunk dominance leads to increased risk of ACL injury in males.

## 2.6 Movement Screening Task

Instability can be defined as the abnormal tendency of a joint to subluxate or dislocate with normal activities and stresses, which can lead to injury.[52] Movement screening tasks have been introduced in an attempt to identify individuals at high risk of injury. These tasks focus on proposed modifiable risk factors for injury to serve as targets for interventions.[16] ACL injuries have been attributed to movements such as landing and/or plant-and-cutting maneuvers, and in a clinical setting certain screening tasks have been developed to replicate such movements including drop landings, hop test, drop vertical jumps, and side-step cutting tasks.[17] The drop vertical jump test a common screening tool often used with 3D motion analysis to predict ACL injuries. [4, 13, 15, 16, 17, 18, 50]

### 2.6.1 Drop Vertical Jump

The drop vertical jump (DVJ) has been suggested to be a successful screening tool to predict ACL injuries.[13, 16-19, 51] It is most often assessed using 3D motion analysis, which has been said to be the gold standard for assessing knee joint moments and angles during activities.[15] The task involves patients standing on a 31cm high box, dropping down from the box onto two separate force plates, and jumping up as high as they can as if to mimic rebounding in basketball.

Jump landing tasks allow clinicians and researchers to screen an individual for risk of ACL injury by evaluating different biomechanics factors during landing. One factor that is consistently identified as the most important is the knee valgus collapse.[12, 13, 15-18, 51] Knee valgus collapse is characterized by hip adduction and internal rotation, knee abduction, anterior tibial translation, and ankle eversion.[13, 14, 51] The combination of these movements results in external KAM, where the proximal tibia moves anterior relative to the femur, and the distal tibia moves away from the midline of the body, contributing to increased strain on the ACL.[15, 51] In 2005, Hewett et al. [12] studied 205 female athletes performing the DVJ. Landing biomechanics were different between individuals who sustained an ACL injury and those who did not. Results showed that abduction moments and angles both contributed to valgus collapse. They observed an abduction angle 8 degrees larger, and an abduction moment 2.5 times greater, in the athletes that had an ACL injury compared to those who did not.[12] Large valgus loading can also lead to increased anterior tibial translation, which contributes to increased load and force on the ACL.[13, 22]

Mok et al.[18] studied 41 elite female handball and soccer players and investigated the within-session and between-session reliability of the moments and angles measured during

DVJ tasks. Their results showed excellent within-session reliability (Intraclass Correlation (ICC) > 0.87), and good to excellent between-session reliability (ICC > 0.69) for all variables except peak internal rotation moment (ICC = 0.40)(47). Gagnon et al.[19] studied the reliability of landing biomechanics measures in16 patients who underwent ACLR. They also reported excellent test re-test reliability with high intraclass correlation for knee abduction angle at initial contact (ICC = 0.81), peak knee abduction angle during the deepest point of landing (ICC = 0.78), and peak KAM (ICC = 0.90).[19]

## 2.7 Summary

Inadequate mechanical and functional stability and re-injury of the reconstructed ACL is a major concern following conventional ACLR, with many patients still experiencing rotational instability of the knee despite surgery. Some studies suggest that persisting instability after ACLR could be due to an injury to the ALL, which usually occurs in conjunction with an ACL tear. In an attempt to combat this instability, there has been a growing interest in combining ACLR with additional anterolateral support with the use of the LET, which is constructed by taking a section of the IT band. There is currently little known about the effect that ACLR combined with LET has on the knee during functionally demanding activities. The DVJ has proven to be an important test of lower limb function in participants at risk of ACL injury. While it is plausible that the LET may benefit or hinder landing biomechanics during a DVJ, this has not been previously investigated.

# Chapter 3

# 3 Methodology

This study was a randomized controlled trial involving a subgroup of patients participating in a larger trial conducted in the Fowler Kennedy Sport Medicine Clinic (FKSMC). Recruitment ran from June 2015 to March 2017. Outcome measures were assessed at 6 and 12 months post-operative. The study was approved by the institution's Research Ethics Board for Health Sciences Research Involving Human Subjects.

## 3.1 Participants

Potential patients had an initial assessment that was completed by one of three surgeons. Patients with an ACL deficient knee were approached during their appointment at the orthopaedic clinic and were provided with a Letter of Information and invited to participate in the study. Patients that were interested were screened to ensure that they met the eligibility criteria. Male and female patients were eligible if they were: between 15 and 25 years of age and willing to undergo ACLR. In addition, patients had to meet at least two of the following criteria: (1) a positive pivot shift of grade 2 or higher in the affected knee; (2) participation in a pivoting sport at a competitive level; (3) generalized ligamentous laxity as defined by a Beighton score of 4 or higher, or genu recurvatum more than 10 degrees.

Patients were excluded from the study if they: (1) underwent previous ACLR on either knee; (2) demonstrated bilateral ACL insufficiency; (3) presented with asymmetric varus knee alignment greater than 3 degrees; (4) presented with an injury where two or more ligaments required surgical repair or reconstruction; (5) had an articular cartilage defect that required treatment other than debridement; (6) did not speak, understand, or read English; or (7) were unwilling to participate.

Patients who met the initial screening criteria were confirmed eligible for the trial by an arthroscopic diagnosis of the knee joint by their surgeon. At the time of arthroscopic surgery, eligible patients were randomized using a computer generated sequence (Empower Health Research, London, ON) by the nursing staff or a research assistant. Patients were randomized on a 1:1 basis: ACLR alone (Control) or ACLR with LET (Experimental). Randomization was carried out in block sizes of two and four, and was stratified by sex, surgeon, and meniscal repair.

## 3.2 Surgical Interventions

Patients randomized to the control group received ACLR alone receiving an autologous hamstring graft. The semitendinosus graft was tripled or quadrupled if it had a diameter of less than 8mm. The anteromedial portal technique was used to drill the femoral tunnel. Femoral fixation of the new graft was completed using an Endobutton, and an interference screw was used for the tibial fixation of the graft.

The patients randomized to the experimental group underwent the same ACLR procedure as the control, but they also received an LET that was fixated on the anterolateral side of the knee. The additional procedure required an oblique incision, running about 5cm, from the lateral epicondyle to Gerdy's tubercle. Leaving the distal attachment of Gerdy's tubercle intact a strip of the IT band measuring 1cm in width and 8cm in length was released, and a #1. Vicryl whip suture was added to the free end of the graft leaving the needle attached. The graft was then tunneled under the LCL where it was fixated to femur with the knee flexed to 70 degrees and the tibia in neutral rotation. Femoral fixation using a Richard's staple was performed immediately distal to the intermuscular septum and proximal to the femoral insertion of the LCL.

Postoperative rehabilitation was the same for each patient regardless of group allocation. The physical therapy department at the FKSMC created the post-operative rehabilitation protocol that focuses on regaining strength and range of motion (Appendix D).

## 3.3 Drop Vertical Jump Test

On the same day that patients had follow-up visits with their surgeon at 6 and 12 months post-ACLR, they also performed the Drop Vertical Jump (DVJ) test in the Wolf Orthopaedic Biomechanics Lab (WOBL). Prior to entering the lab, patients put on a fabric sleeve over their surgical scars on the surgical knee to blind the researchers to group allocation. For the DVJ test, the patient was instructed to: (1) drop down from the box with both feet at the same time; (2) as soon as you land on the force plates with both feet, jump straight up as high as you can; and (3) land back on the force plates. Patients were asked to complete two practice jumps. Patients then performed five good jumps, as defined by landing directly on the force plates. The box height was 31cm.

## 3.4 Testing Procedure

Data from all five jumps were collected using an 11-camera 3D motion capture system (EvaRT, Motion Analysis Corporation, Santa Rosa, USA) and two force plates embedded in the ground (Advanced Mechanical Technology Inc., Watertown, MA). Each day before testing was completed, the cameras were calibrated and the force plates were zeroed. Patients were set up with a modified Helen Hayes marker set with four additional markers; one on each of the greater trochanters, the spinous process of the tenth thoracic vertebra (T10), and the right scapula.

To calculate virtual joint centers, markers were placed bilaterally on the medial knee joint lines and on medial malleoli. The medial knee joint line markers were removed for the DVJ testing. Two trained researchers, blinded to the patient group allocation, assessed all DVJ testing. While one researcher operated the computer system, the other was responsible for explaining the jump protocol, completing a data collection form, and ensuring the jumps were executed correctly. Data collection began with the patient performing two 3-second static trials standing stationary on the force plate. The third static trial was completed with the patient standing on the box for 3 seconds (Figure 1). Once all static trials were completed, the patient completed five DVJ trials. If any of the five jumps did not meet the criteria for a valid jump (i.e. they left the box with both feet at the same time, rebounded as high as they could, and landed with each foot completely hitting the separate force plates), then additional trials were performed (Figure 2). Camera and force plate data were collected at 120Hz and 1200Hz, respectively, during the DVJ trials.

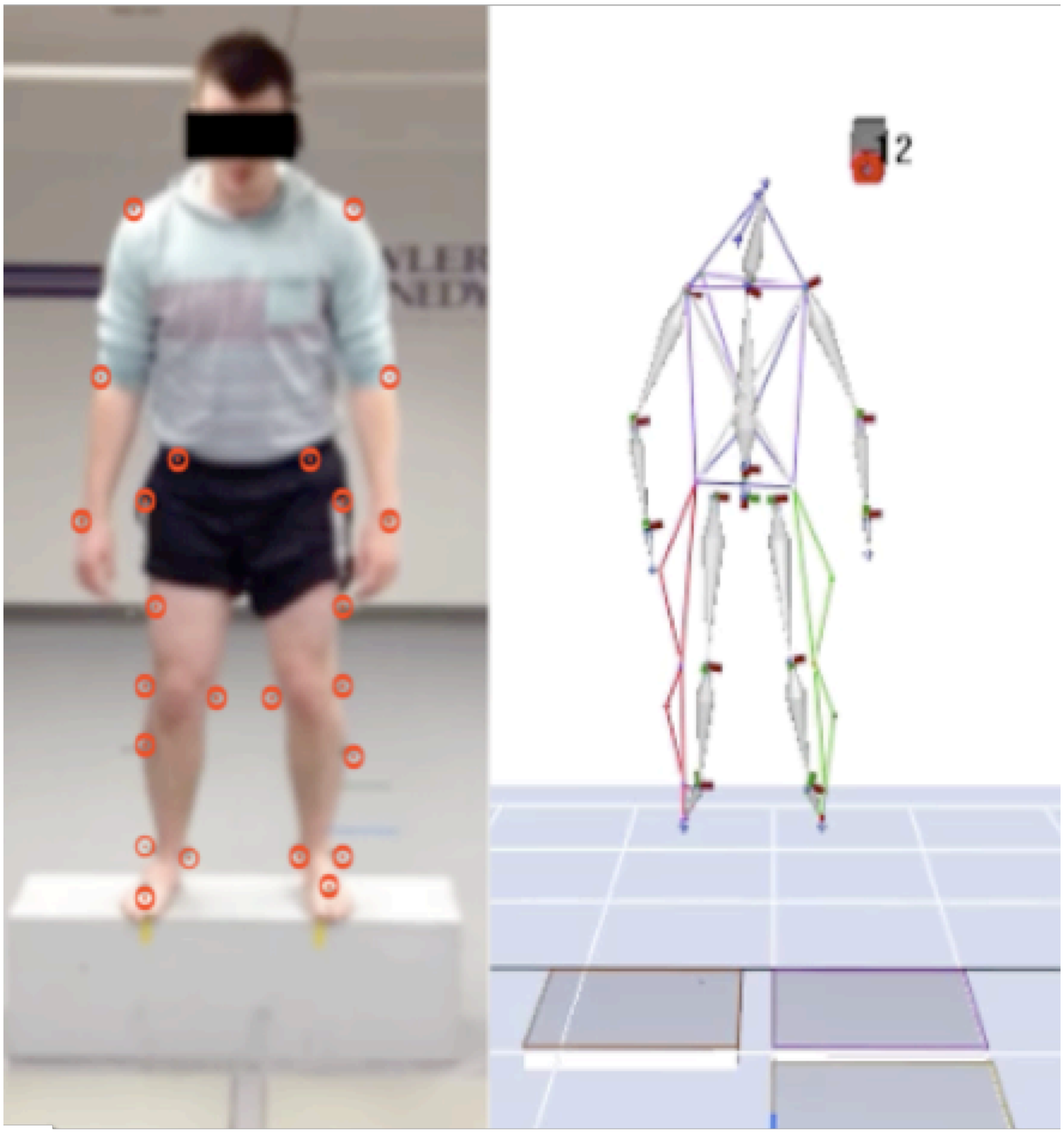


Figure. 1 Picture of a patient completing a static trial with the corresponding view as seen in the software used for data analysis (Cortex 5.0, Motion Analysis Corporation, Santa Rosa, CA).

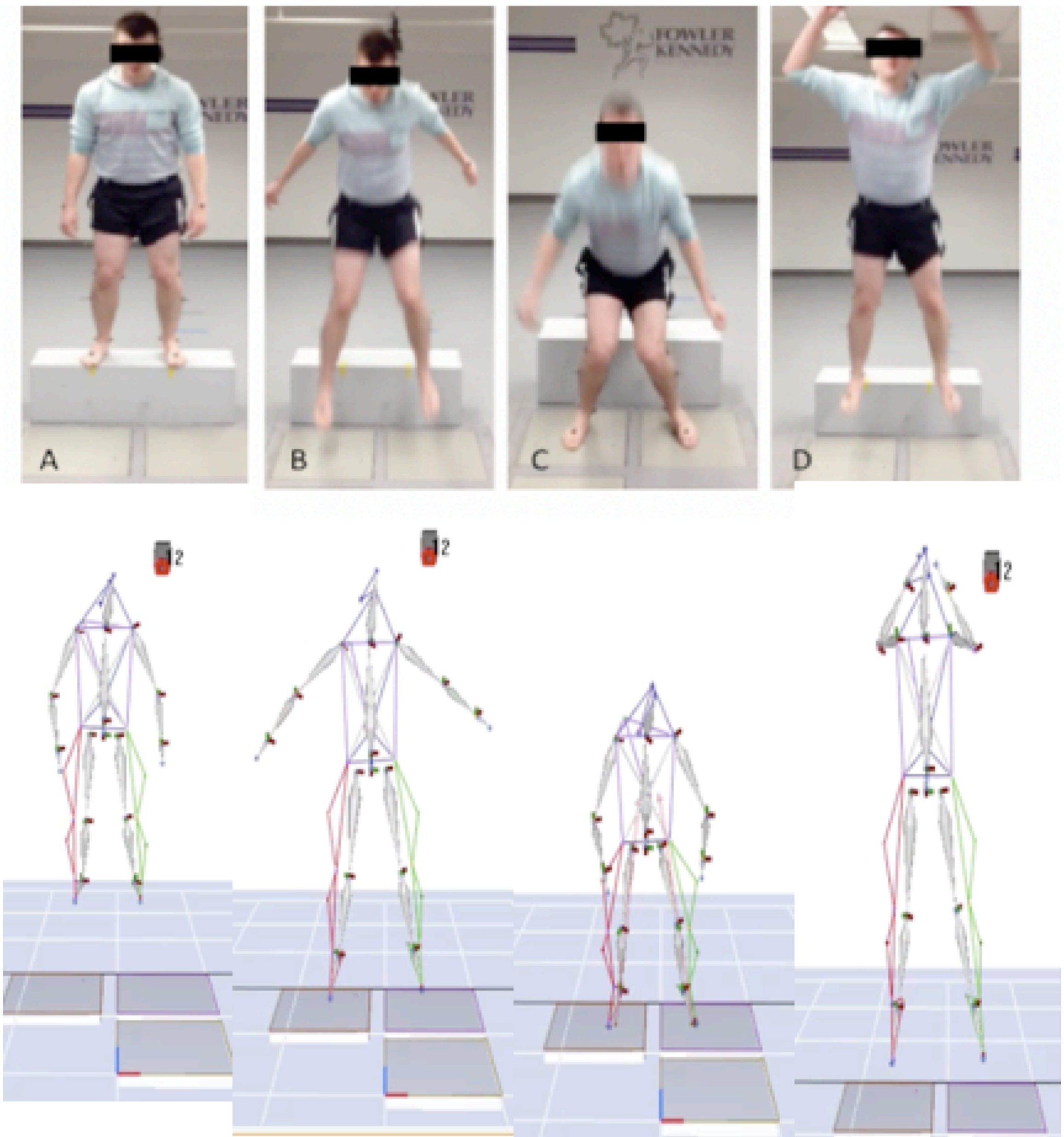


Figure 2. Still captures of a patient during the various stages of the DVJ with the corresponding snapshots as seen in the software used for data analysis (Cortex 5.0, Motion Analysis Corporation, Santa Rosa, CA).

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### 3.4.1 Data Processing and Analyses

Once testing was complete, the researcher tracked one static trial on the force plate as well as the static trial on the box (Cortex 5.0, Motion Analysis Corporation, Santa Rosa, CA, USA). The static trials were used to determine relative marker orientation, calculate body mass and virtual joint centres for the hip, knee, and ankle. The information saved from the static trials was applied to the dynamic trials to create body segments, calculated from one marker centre to another, based on individual height, weight and sex (Cortex 5.0, Motion Analysis Corporation, Santa Rosa, CA, USA). Force plate data from initial contact with the ground to toe-off was filtered at 100 Hz, and was processed using a Butterworth filter with an input frequency of 12 Hz.

The external moments about the knee joint were calculated using inverse dynamics (Cortex 5.0, Motion Analysis Corporation, Santa Rosa, CA, USA). The ground reaction force (GRF), external knee joint moments and knee joint angles during landing were plotted over 100% of the stance phase, and the peak values were identified. Peak values for all variables were expressed as the mean of three trials

## 3.5 Outcome Measures

The primary outcome was the peak KAM. Secondary outcomes included the peak knee flexion moment (KFM), peak knee internal rotation moment (KIRM), peak vertical ground reaction force (VGRF), peak knee abduction angle (KAA), peak knee flexion angle (KFA), and peak knee internal rotation angle (KIRA).

## 3.6 Sample Size

This study was designed as an equality study and the sample size calculation was completed accordingly. Pilot data suggested a standard deviation of 17 Nm. Based on a comparison of two independent groups and a two-sided alpha of 0.05, a sample size of 140 patients (70 per group) would provide 80% statistical power to detect a between difference as small as 7 Nm. To account for approximately 10% loss to follow-up, we recruited 154 patients (Appendix A).

## 3.7 Statistical Analysis

For each outcome measure, we completed an independent-samples t-test to compare the means for the surgical limb between the ACL alone group and the ACL plus LET group. We conducted separate analyses for those patients with 6 month data, 12-month data, and both 6 and 12-month data. We calculated means and standard deviations for both groups, and the mean differences between groups with 95% confidence intervals. Statistical significance was set at $p \leq 0.05$. We used SPSS Statistics Version 24.0 (California, USA) for all analyses.

# Chapter 4

## 4 Results

We recruited 154 patients from the larger FKSMC study. We randomized 76 patients to the ACL alone (Control) group and 78 patients to the ACL plus LET (Experimental) group (Figure 3).

In the ACL only group 46 (60%) patients completed testing at 6 months, 59 (77%) patients completed testing at 12 months, and 39 (51%) patients had data at both time points. In the ACL plus LET group 44 (56%) patients completed testing at 6 months, 61 (78%) patients completed testing at 12 months, and 38 (48%) patients had data at both time points. Baseline characteristics of all the patients involved are described in Table 1.

At six months, there were 46 ACL (male = 21, female = 25) patients and 44 ACL plus LET (males = 17, females = 27) patients who completed testing. There were no statistically significant differences in landing biomechanics between groups (Table 2).

At twelve months, there were 59 ACL (male = 22, female = 37) patients and 61 ACL plus LET (males = 24, females = 38) patients who completed testing. There were no statistically significant differences in landing biomechanics between groups (Table 3).

There were 77 patients (ACL = 39, ACL + LET = 38) that completed testing at both six and twelve months. There were no statistically differences in landing mechanics between groups at either time point (Table 4).

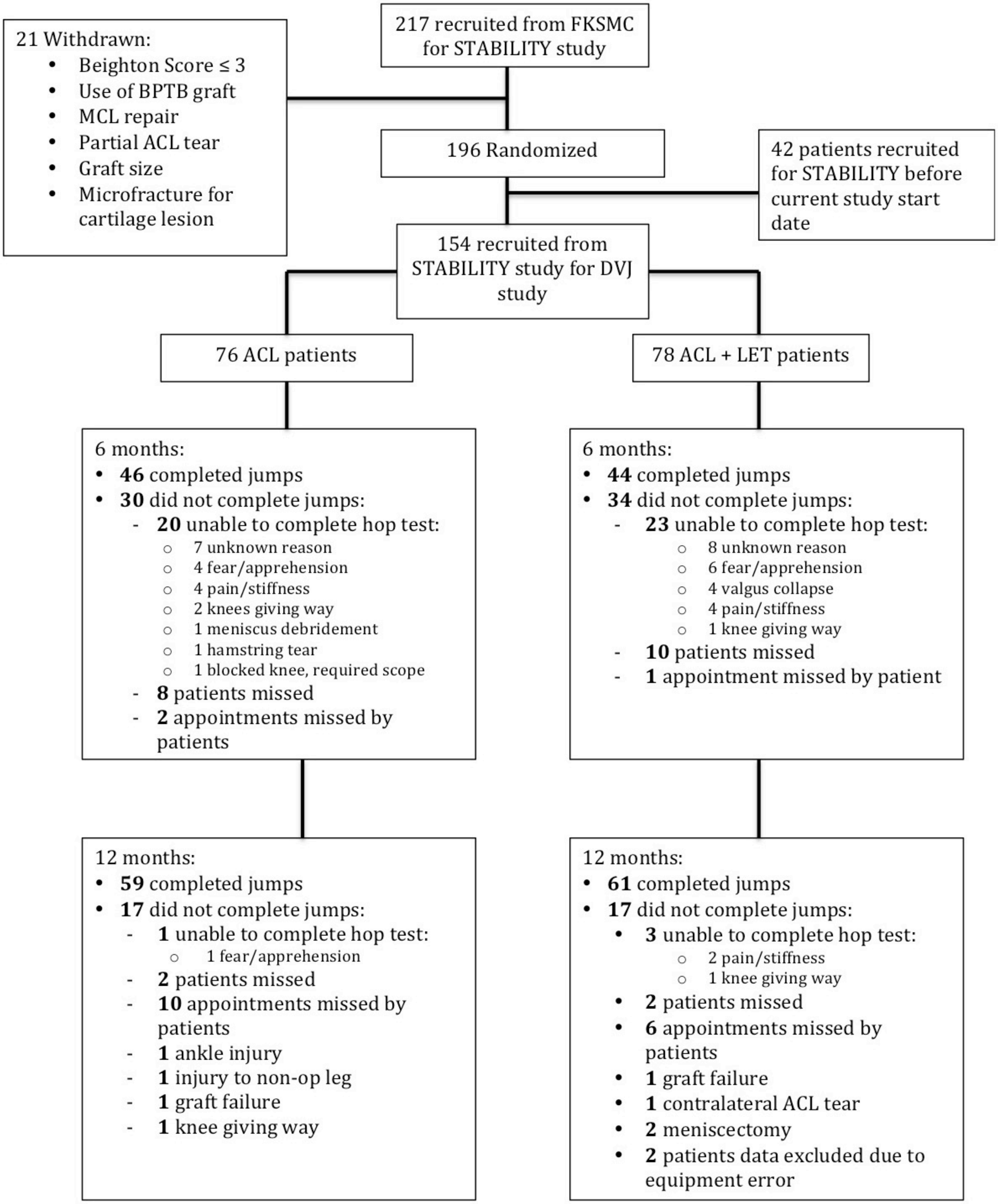


Figure 3. Participant flow through the study

Table 1. Participant Baseline Characteristics (mean ± SD (min – max))

| | Patients with 6 month data | | Patients with 12 month data | | Patients with both 6 & 12 month data | |
|---|---|---|---|---|---|---|
| | ACL (n = 46) | ACL + LET (n = 44) | ACL (n = 59) | ACL + LET (n = 61) | ACL (n = 39) | ACL + LET (n = 38) |
| **Age (yrs)** | 21.5 ± 2.5 (19.0 - 24.0) | 20.7 ± 2.9 (17.8 - 23.6) | 21.5 ± 2.8 (18.7 - 24.3) | 21.6 ± 3.0 (18.6 - 24.6) | 21.4 ± 2.5 (18.9 - 23.9) | 20.5 ± 2.7 (17.8 - 23.2) |
| **Height (cm)** | 173.4 ± 9.8 (163.6 - 183.2) | 171.2 ± 9.3 (161.9 - 180.5) | 171.7 ± 9.3 (162.4 - 181.0) | 171.4 ± 9.2 (162.2 - 180.6) | 172.9 ± 9.8 (163.1 - 182.7) | 171. ± 9.6 (161.5 - 180.7) |
| **Mass (kg)** | 75.1 ± 14.5 (60.6 - 89.6) | 72.1 ± 14.7 (57.4 - 86.8) | 72.7 ± 14.3 (58.4 - 87.0) | 73.9 ± 16.1 (57.8 - 90.0) | 75.0 ± 15.3 (59.7 - 90.3) | 71.9 ± 14.9 (57.0 - 86.8) |
| **BMI* ($kg/m^2$)** | 25.0 ± 4.2 (20.7 -29.7) | 24.4 ± 3.7 (20.7 - 28.1) | 24.6 ± 4.1 (20.5 - 28.7) | 24.8 ± 3.9 (20.9 - 28.7) | 25.1 ± 4.5 (20.6 - 29.6) | 24.4 ± 3.8 (20.6 - 28.2) |
| **Baseline KOOS Score** | 60.1 ± 15.7 (44.4 - 75.8) | 59.7 ± 15.8 (43.9 - 75.5) | 58.8 ± 15.1 (43.7 - 73.9) | 60.8 ± 14.7 (46.1 - 75.5) | 59.9 ± 15.8 (44.1 - 75.7) | 59.0 ± 16.5 (42.5 - 75.5) |
| **Males** | 21 | 17 | 22 | 24 | 16 | 15 |
| **Females** | 25 | 27 | 37 | 38 | 23 | 23 |
| **Affected Limb** | | | | | | |
| Left | 22 | 21 | 31 | 31 | 19 | 17 |
| Right | 24 | 23 | 28 | 31 | 20 | 21 |
| **Dominant Leg** | | | | | | |
| Left | 5 | 2 | 8 | 4 | 5 | 2 |
| Right | 41 | 42 | 51 | 58 | 34 | 36 |
| **Injured during sport** | | | | | | |
| No | 3 | 1 | 5 | 2 | 3 | 1 |
| Yes | 43 | 43 | 54 | 60 | 36 | 37 |
| **Injury during sport participation** | | | | | | |
| Football | 1 | 7 | 0 | 7 | 0 | 5 |
| Basketball | 8 | 3 | 9 | 4 | 7 | 3 |
| Volleyball | 4 | 2 | 6 | 2 | 4 | 2 |
| Downhill Skiing | 0 | 1 | 0 | 1 | 0 | 1 |
| Baseball/Softball | 1 | 0 | 2 | 0 | 1 | 0 |
| Soccer | 19 | 24 | 26 | 34 | 17 | 21 |
| Hockey | 0 | 0 | 2 | 0 | 0 | 0 |
| Rugby | 3 | 4 | 3 | 8 | 2 | 4 |
| Other | 7 | 2 | 6 | 4 | 5 | 1 |

*BMI = Body Mass Index

**Table 2. Knee moments, vertical ground reaction force, and knee angles for patients who completed jumps at 6 months post surgery in the ACL alone group and ACL plus LET group. A comparison of the surgical limb between groups.**

| | ACL Alone (N = 46) Mean ± SD | ACL plus LET (N = 44) Mean ± SD | Mean Difference (95% CI) | p-Value |
|---|---|---|---|---|
| Peak KAM (Nm) | 18.05 ± 13.16 | 22.11 ± 14.44 | -4.05 (-9.83 – 1.73) | 0.16 |
| Peak KFM (Nm) | 94.43 ± 25.27 | 95.83 ± 36.41 | -1.39 (-14.47 – 11.69) | 0.83 |
| Peak KIRM (Nm) | 10.67 ± 7.60 | 12.28 ± 8.50 | -1.60 (-4.98 – 1.77) | 0.34 |
| Peak VGRF (N) | 969.94 ± 269.01 | 899.62 ± 231.24 | 70.31 (-34.97 – 175.61) | 0.18 |
| Peak KAA (°) | 6.61 ± 8.92 | 5.37 ± 8.19 | 1.24 (-2.34 – 4.83) | 0.49 |
| Peak KFA (°) | 80.47 ± 15.10 | 80.42 ± 15.35 | 0.05 (-6.33 – 6.43) | 0.98 |
| Peak KIRA (°) | 21.83 ± 20.04 | 18.85 ± 16.40 | 2.98 (-4.71 – 10.77) | 0.44 |

SD = Standard Deviation, CI = confidence intervals, KAM = knee abduction moment, KFM = knee flexion moment, KRM = knee internal rotation moment, VGRF = vertical ground reaction force, KAA = knee abduction angle, KFA = knee flexion angle, KIRA = knee internal rotation angle

**Table 3. Knee moments, vertical ground reaction force, and knee angles for patients who completed jumps at 12 months post surgery in the ACL alone group and ACL plus LET group. A comparison of the surgical limb between groups**

| | ACL Alone (N = 59) Mean ± SD | ACL plus LET (N = 61) Mean ± SD | Mean Difference (95% CI) | p-Value |
|---|---|---|---|---|
| Peak KAM (Nm) | 21.64 ± 14.06 | 21.62 ± 13.08 | 0.01 (-4.87 – 4.90) | 0.99 |
| Peak KFM (Nm) | 85.21 ± 29.23 | 79.67 ± 31.85 | 5.54 (-5.48 – 16.56) | 0.32 |
| Peak KIRM (Nm) | 9.25 ± 5.82 | 11.09 ± 7.54 | -1.83 (-4.26 – 0.59) | 0.13 |
| Peak VGRF (N) | 953.66 ± 258.24 | 942.69 ± 247.61 | 10.97 (-80.10 – 102.04) | 0.81 |
| Peak KAA (°) | 4.25 ± 7.52 | 3.84 ± 9.34 | 0.40 (-2.65 – 3.47) | 0.79 |
| Peak KFA (°) | 88.12 ± 17.76 | 83.50 ± 13.93 | 4.61 (-1.11 – 10.35) | 0.11 |
| Peak KIRA (°) | 34.70 ± 13.28 | 35.22 ± 15.74 | -0.52 (-5.78 – 4.73) | 0.84 |

SD = Standard Deviation, CI = confidence intervals, KAM = knee abduction moment, KFM = knee flexion moment, KIRM = knee internal rotation moment, VGRF = vertical ground reaction force, KAA = knee abduction angle, KFA = knee flexion angle, KIRA = knee internal rotation angle

**Table 4. Knee moments, vertical ground reaction force, and knee angles for patients who completed jumps at 6 and 12 months post surgery in the ACL alone group and ACL plus LET group. A comparison of the surgical limb between groups.**

| | ACL Alone (N = 39) Mean ± SD | ACL plus LET (N = 38) Mean ± SD | Mean Difference (95% CI) | p-Value |
|---|---|---|---|---|
| **6 months** | | | | |
| Peak KAM (Nm) | 18.07 ± 13.03 | 22.22 ± 14.30 | -4.15 (-10.36 – 2.05) | 0.18 |
| Peak KFM (Nm) | 92.60 ± 25.49 | 96.51 ± 35.48 | -3.91 (-17.91 – 10.08) | 0.57 |
| Peak KIRM (Nm) | 11.05 ± 7.99 | 12.14 ± 8.73 | -1.08 (-4.88 – 2.71) | 0.57 |
| Peak VGRF (N) | 987.50 ± 218.61 | 927.44 ± 237.07 | 60.06 (-57.98 – 178.11) | 0.31 |
| Peak KAA (°) | 7.37 ± 8.94 | 5.37 ± 8.13 | 2.00 (-1.87 – 5.89) | 0.30 |
| Peak KFA (°) | 81.10 ± 14.73 | 80.14 ± 16.14 | 0.96 (-6.05 – 7.97) | 0.78 |
| Peak KIRA (°) | 21.94 ± 20.57 | 19.72 ± 15.37 | 2.22 (-6.03 – 10.48) | 0.59 |
| **12 months** | | | | |
| Peak KAM (Nm) | 22.65 ± 15.63 | 20.72 ± 13.79 | 1.92 (-4.77 – 8.63) | 0.56 |
| Peak KFM (Nm) | 89.58 ± 30.89 | 78.99 ± 5.32.72 | 10.58 ± (-3.85 – 25.03) | 0.14 |
| Peak KIRM (Nm) | 9.35 ± 5.89 | 10.60 ± 6.46 | -1.24 (-4.05 – 1.56) | 0.38 |
| Peak VGRF (N) | 987.50 ± 271.87 | 927.44 ± 247.15 | 60.06 (-57.98 – 178.11) | 0.31 |
| Peak KAA (°) | 5.80 ± 7.08 | 5.11 ± 9.45 | 0.694 (-3.09 – 4.48) | 0.71 |
| Peak KFA (°) | 87.12 ± 16.65 | 82.59 ± 15.94 | 4.52 (-2.87 – 11.93) | 0.22 |
| Peak KIRA (°) | 35.88 ± 13.67 | 33.36 ± 16.40 | 2.52 (-4.32 – 9.37) | 0.46 |

SD = Standard Deviation, CI = confidence intervals, KAM = knee abduction moment, KFM = knee flexion moment, KIRM = knee internal rotation moment, VGRF = vertical ground reaction force, KAA = knee abduction angle, KFA = knee flexion angle, KIRA = knee internal rotation angle

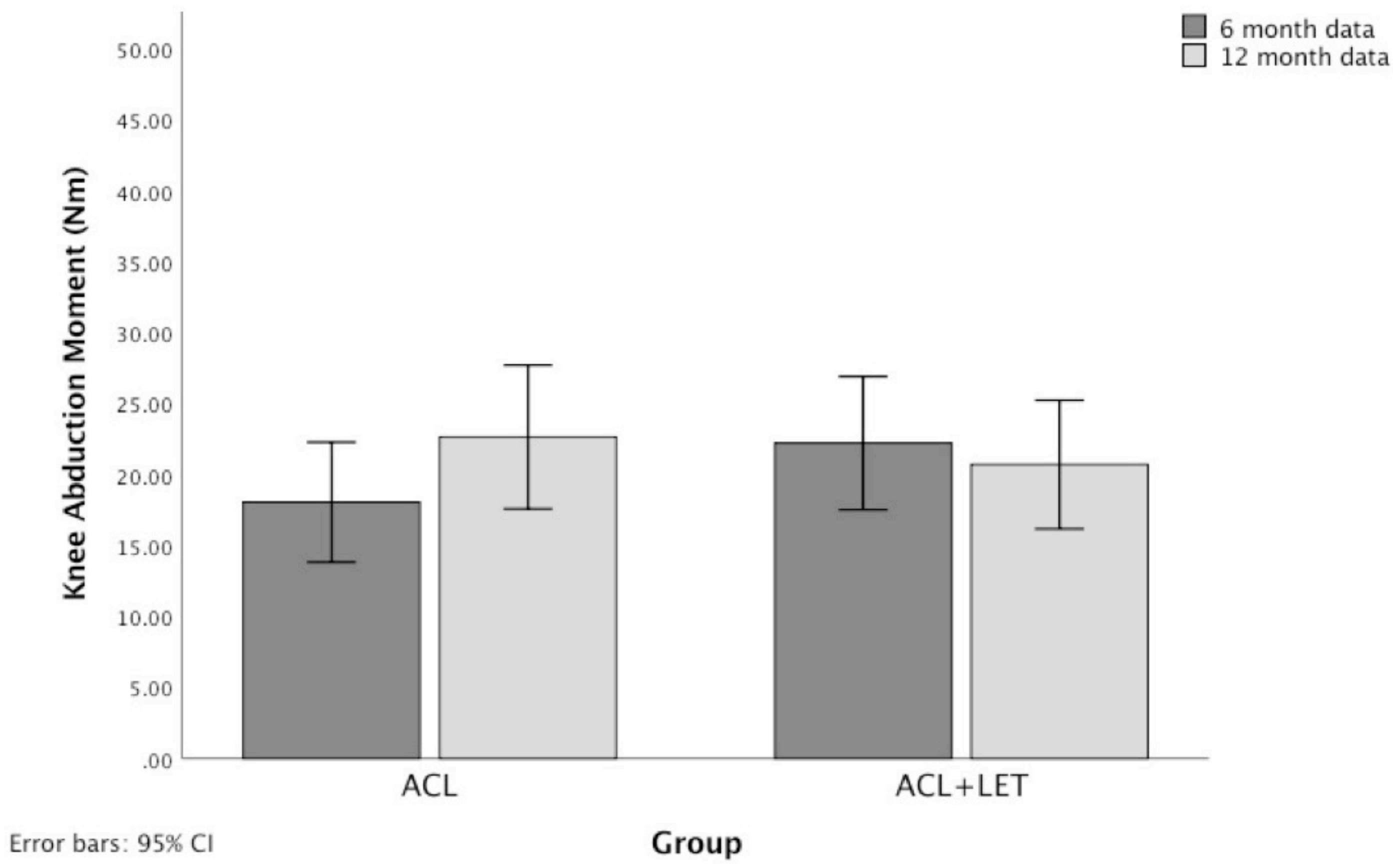


Figure 4. Means and 95% confidence intervals for peak knee abduction moment between groups for all patients with 6 month data and all patients with 12 month data.

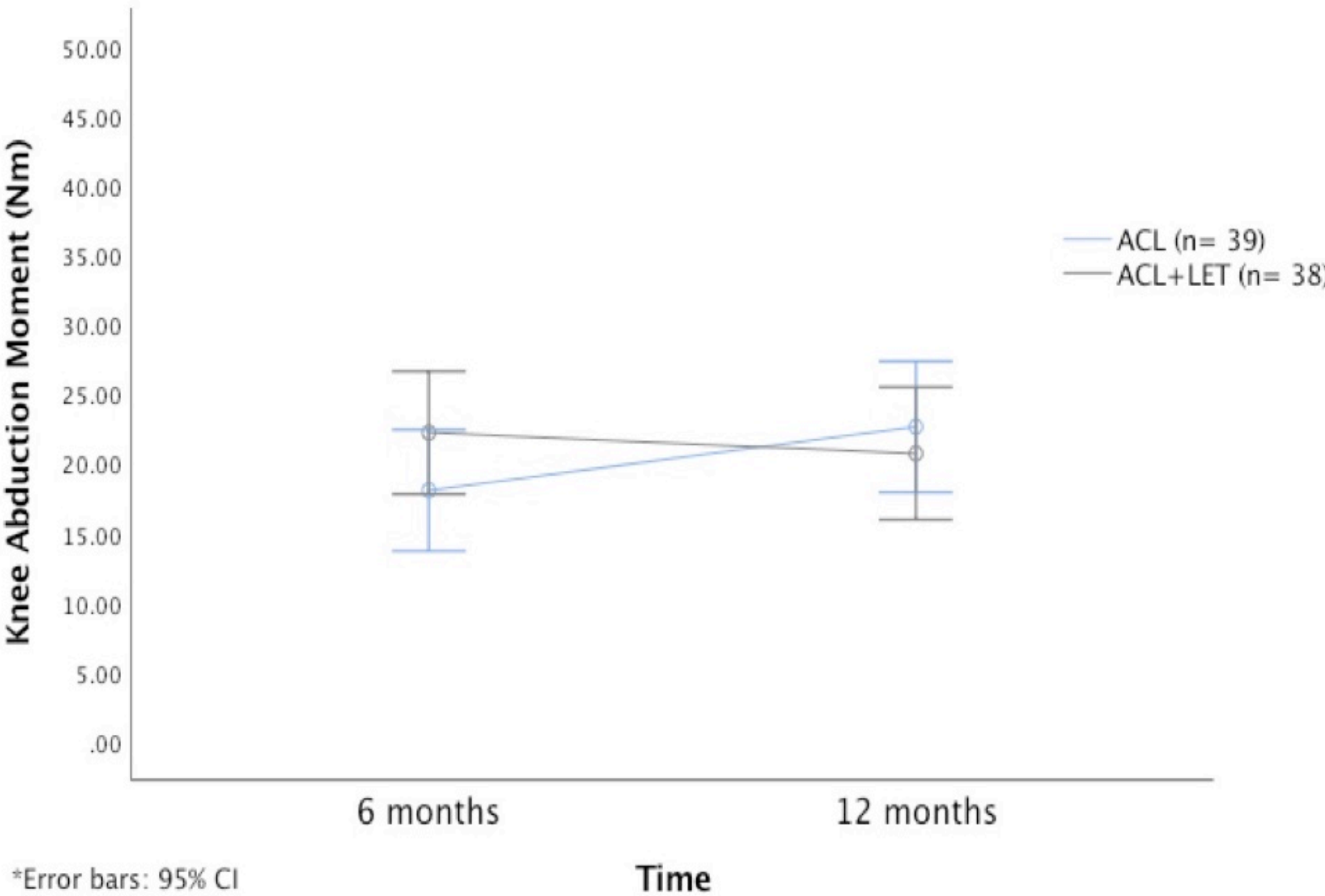


Figure 5. Means and 95% confidence intervals for peak knee abduction moment at 6 and 12 months for patients that completed jumps at both time points.

# Chapter 5

## 5 Discussion

A continuing concern following ACL reconstruction is the inability to restore normal knee biomechanics, which has led to an increased interest in implementing extra-articular augmentation. [3, 31, 32] The purpose of this randomized trial was to determine if there was a difference in landing biomechanics at 6 and 12 months post surgery between patients who received ACL reconstruction alone and those who received ACL reconstruction with the addition of the LET.

There are a number of knee biomechanical abnormalities during a DVJ suggested to increase risk of ACL tears.[14, 17] The findings of this study suggested no statistically significant difference in these landing biomechanics between ACL alone and ACL plus LET.

The main outcome of interest was the peak KAM as it is a well documented factor in predicting ACL injury, with excellent test re-test reliability during drop vertical jump tasks.[12, 13, 15, 16-19] Large KAMs have been associated with greater knee valgus collapse and increased anterior tibial translation.[10, 12, 13, 20, 21, 22] If a large KAM was observed in a patient who received the LET, it is possible that the integrity of the IT band had been compromised resulting in greater anterior tibial translation in addition to a large KAM, which increases that individuals risk of ACL re-injury. Myer et al.[22] reported that individuals with a high KAM (>25.3 Nm) had a 6.8% chance of ACL injury compared a 0.4% chance if the moment was below this ACL risk threshold. In each of our separate analyses, neither the ACL alone group nor the ACL plus LET group had a mean peak KAM above the 25.3 Nm threshold proposed by Myer et al.[22] At 6 months, 21% (10/46) of patients in the ACL alone group and 29% (13/44) in the ACL plus LET group had a peak KAM > 25.3Nm. At 12 months, 30% (18/59) in the ACL alone group, and 32% (20/61) in the ACL plus LET had a peak KAM > 25.3 Nm. These findings suggest that the majority of patients, regardless of procedures, demonstrated safe frontal plane moments during a drop vertical jump task.

In the analysis of the patients at 6 month post operation, the ACL group had a lower mean peak KAM compared to the ACL plus LET group, but the difference did not reach statistical significance. The 95% CI indicates that the difference could be as large as 9 Nm, which is likely not clinically important.

Similar results were observed with the analysis of the patients who had both 6 and 12 months data (Table 4). At 12 months the mean difference between groups in peak KAM was very small. These finding are consistent with muscular strength differences reported by Getgood et al.[3] They found that patients who received the ACL plus LET procedure had less muscular strength at 6 months compared to the ACL alone group, which may have been a contributing factor to a greater KAM. Results were no longer different at 12 months.

The knee abduction angle during a DVJ is also an important factor when screening for increased risk of ACL injury.[14, 22, 46, 47] All of our results suggested no significant difference in KAA between the ACL alone and the ACL plus LET group. Interestingly, the mean peak KAA in both groups at both follow-ups was slightly higher than the mean KAA reported by Hewett et al. in uninjured ACL knees (1.4°).[13]

We also observed no statistically significant differences in the sagittal plane variables in either group at 6 and 12 months post-surgery. Specifically, the mean differences in peak KFM suggested no statistically significant difference between the ACL alone and ACL plus LET. Knee flexion angle is suggested to be a good predictor of ACL injuries and is often described as a stiff landing, where the knee is maintained in greater extension.[15] Hewett et al. investigated mean flexion angles between ACL injured knees (n = 9) and non-injured knees (n = 390), and suggested knee flexion of 82.4° is the ideal angle to avoid injury.[13-15] Our results show mean KFA that are relatively close to the 82.4°, suggesting that both procedures may allow for good range of motion that contributes to a reduced risk of ACL injury. However the width of the confidence intervals must be taken into consideration when determining the true values of the mean KFA.

Lastly, we did not find any statistically significant differences in the analysis of transverse moments and angles between groups at 6 and 12 months post-surgery. However, potential inaccuracy of the present methods and its ability to quantify tibiofemoral rotation must be acknowledged.[50] The use of superficial markers placed on the skin and clothing are used to calculate virtual joint centers and predict bony movements. These results are most likely an over-estimation of true transverse plane rotation angles at the knees.[18]

## 5.1 Limitations

A limitation of this study is the number of patients that were recruited, but only jumped at one of the time points. Reasons for not participating included injury, perception that they were unable to complete a hop test, or missed appointments. Another limitation may be the generalizability of the present sample. The majority of patients were soccer players that were treated by orthopaedic surgeons at a tertiary care centre specializing in sport medicine. The generalizability of the present sample to non-elite athletes or to other tertiary centres is unclear.

Although 3D motion movement analysis are considered the gold standard for assessing functional lower extremity biomechanics, the present methods may not have detect more subtle differences in knee joint biomechanics.[13, 15, 188, 22, 50]

Similarly, although the DVJ test is appropriate to evaluate the degree of valgus collapse and ACL risk, other activities involving more anterior tibial translation and/or internal rotation many reveal differences between the surgical procedures not observed with the DVJ.[12, 13, 15, 16-18]

# Chapter 6

## 6 Summary and Conclusion

Following ACLR, the potential for inadequate rotational stability and re-injury remains. The LET in addition to ACLR is intended to add stability to the knee, yet the procedure compromises lateral knee soft tissues that may affect performance during functionally demanding activities. Using the DVJ test we found no significant difference in peak knee moments, peak vertical ground reaction force, or peak knee angles at 6 and 12 months post-surgery between patients randomized to ACLR alone or to ACLR plus LET. The current study suggests that the LET does not hinder or benefit landing biomechanics.

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# Appendices

## Appendix A: Sample Size Calculation

Z score, 2-sided alpha = 1.96

Z score, 80% power = 0.84

Estimated Standard deviation ($\sigma$) = 17 Nm

Estimated Mean Difference ($\delta$) = 8 Nm

Sample Size Calculation for an equality study:

$$N/group = \frac{2(Z_{\alpha/2} + Z_{\beta})^2 \sigma^2}{\delta^2}$$

$$= \frac{2(1.96 + 0.84)(17)^2}{(8)^2}$$

$$= 70 \text{ per/group}$$

## Appendix B: University of Western Research Ethics Broad Approval

Western Research — Research Ethics

**Western University Health Science Research Ethics Board**
**HSREB Amendment Approval Notice**

**Principal Investigator**: Dr. Alan Getgood
**Department & Institution**: Schulich School of Medicine and Dentistry\Surgery,Western University

**Review Type**: Full Board
**HSREB File Number**: 104524
**Study Title**: Multicenter Randomized Clinical Trial comparing Anterior Cruciate Ligament Reconstruction With and Without Lateral Extra-articular Tenodesis in Individuals Who Are At High Risk of Graft Failure.
**Sponsor**:

**HSREB Amendment Approval Date**: May 29, 2015
**HSREB Expiry Date**: November 05, 2015

**Documents Approved and/or Received for Information**:

| Document Name | Comments | Version Date |
|---|---|---|
| Other | FABQ | 2015/05/19 |
| Revised Western University Protocol | | 2015/05/29 |
| Revised Letter of Information & Consent | | 2015/05/19 |

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the amendment to the above named study, as of the HSREB Initial Approval Date noted above.

HSREB approval for this study remains valid until the HSREB Expiry Date noted above, conditional to timely submission and acceptance of HSREB Continuing Ethics Review.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice Practices (ICH E6 R1), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number [redacted]

Ethics Officer, on behalf of Dr. Joseph Gilbert, HSREB Chair

Ethics Officer to Contact for Further Information

| | | | |
|---|---|---|---|
| ___ Erika Basile ebasile@uwo.ca | ___ Grace Kelly grace.kelly@uwo.ca | ___ Mina Mekhail mmekhail@uwo.ca | Vikki Tran vikki.tran@uwo.ca |

*This is an official document. Please retain the original in your files.*

[redacted]

## Appendix C: Letter of Information

### LETTER OF INFORMATION

**Title of Research:**
Multicenter Randomized Clinical Trial comparing Anterior Cruciate Ligament Reconstruction With and Without Lateral Extra-articular Tenodesis in Individuals Who Are At High Risk of Graft Failure.

**Lead Researchers:**
Dr. Alan Getgood
Fowler Kennedy Sport Medicine Clinic, Western University
[redacted]

Dr. Dianne Bryant
Elborn College, Western University
[redacted]

**Study Sponsors:**
International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS)
Orthopaedic Research and Education Foundation (OREF)

**Information:**
You are being invited to participate in a research study because your surgeon has determined that you have a torn anterior cruciate ligament (ACL) and you have elected to undergo surgery to reconstruct this ligament. The purpose of this letter is to provide you with information required for you to make an informed decision regarding participation in this research.

The purpose of this study is to compare outcomes (function, strength, range of motion and quality of life) between patients who receive the usual anterior cruciate ligament (ACL) reconstructive surgery to patients who receive anterior cruciate ligament reconstructive surgery with a lateral extra-articular tenodesis. A lateral extra-articular tenodesis is the creation of a new ligament-like structure using a piece of the Iliotibial (IT) band on the outside of the knee. The usual standard of care for an ACL tear is ACL reconstruction without this lateral extra-articular tenodesis (new ligament-like structure). Some studies have shown high graft failure rates (ACL re-tear) in young individuals who return to pivoting contact sports following ACL reconstruction. This study is designed to look at whether or not adding this extra structure reduces the risk of graft failure in this population. To determine whether one procedure is better than the other, we must randomize (like flipping a coin) you into one of the surgery groups. Six hundred (600) patients will take part in this study at different centres around the world. This centre will recruit one hundred (200) patients; approximately 100 per group.

**Eligibility:**
To participate in this study you must be 25 years of age or younger. You cannot have had

previous ACL reconstruction on either knee. You cannot have a multi-ligament injury (two or more ligaments requiring surgery). If you are currently participating in another research study, you must inform your surgeon and the research assistant.

**Explanation of the Study Procedures:**
The goal of anterior cruciate ligament reconstruction surgery is to replace the torn ACL with a tissue graft to provide stability to the knee. This is done through a surgical procedure that is performed arthroscopically (with a camera). Either spinal or general anesthesia is used. Small screws are placed into the bone to hold the tissue graft in place.

If, during the surgery, your surgeon determines that your knee does not meet the requirements for the study i.e. other ligaments are found to be torn, or it cannot be treated using the surgical procedure defined in the study protocol, he/she will withdraw you from the study and you will be treated according to standard practice of your surgeon.

**Description of the Study:**
The total time commitment of the study is two years. Visits for this study will coincide with follow-up visits that you would already attend with your surgeon after your surgery. Each visit with the surgeon will take approximately 40 minutes of your time. Before your surgery, you will be asked to complete ten questionnaires along with a strength assessment, hop test and range of motion measurement. Following your surgery you will receive instructions to undergo standardized physical therapy. You will be given a Rehabilitation Guide to give to your physical therapist.

After surgery, you will come in for an appointment with your surgeon at 3 months, 6 months, 1 year and 2 years where you will be asked to complete the same nine questionnaires. At that time, we will also measure your range of motion. Completing these questionnaires will take approximately 15 - 20 minutes of your time and collection of range of motion measurements, strength and hop testing will take approximately 45 minutes.

At 6 months, 1 year and 2 years post - surgery, we will measure your strength and assess your ability to perform a series of simple jumping tasks. Strength tests will be performed by bending and extending your knee 3 times to measure your strength against resistance. This is done using a computerized machine called an isokinetic dynamometer. During each test session, you will be seated with your back against a backrest with a seat belt securing you into place.

The jumping tests are subdivided into functional tests and biomechanical assessment. The functional tests include a single hop for distance, a timed 6 metre hop test, a triple hop for distance and a crossover hop for distance. The biomechanical assessment will use motion analysis equipment to look at the mechanics of your knee as you perform a vertical jumping task.

The single hop for distance test is performed by having you stand on your leg to be tested, and hop forward on the same leg. The timed 6 metre hop test is performed by having you perform large one - legged hops in series over the 6 metres. The triple hops for distance test is performed by having you stand on one leg and perform three hops in a row on the same leg, landing as far away as possible. The crossover hop for distance is performed by having you hop forward three times while making a "Z' pattern.

The biomechanical assessment will take place in the Wolf Orthopaedic Biomechanics Laboratory (WOBL) at the Fowler Kennedy Sports Medicine Clinic. The task will require you to jump onto a force plate while sensors monitor your movements and muscle activity. These sensors will be placed on your skin over your feet, knees, hips, arms and shoulders using double-sided tape. You will be asked to wear shorts (or tights) and a T-shirt or tank top in order to assist with the placement of these sensors. Although they are easily removed, the tape may cause some pulling of hair therefore we may ask to shave some areas with a plastic disposable razor in order to limit discomfort.

After becoming familiarized with the instrumentation we will ask you to perform a double leg drop vertical jump. This task will require you to drop/hop off a box (at an elevated height of 31cm) and land with both legs on a force plate outlined on the ground, following which you will immediately jump vertically as high as you can, as if rebounding a basketball.

**Alternatives to Participation:**
If you do not choose to participate in this study, you will receive the usual ACL reconstructive surgery provided by your surgeon.

**Risks:**
You could fall, injure or re - injure yourself while performing tests, however, the risks are no greater than those encountered with typical postoperative rehab protocols. There are no other known health risks associated with this study.

**Benefits:**
There are no direct benefits to you for participating in this study; however your participation will help inform surgeons and physiotherapists as to which surgical procedure offers patients who undergo ACL reconstruction the best outcome.

**Cost/Compensation:**
You will not be compensated for your participation in this study, however, you will not be required to pay for parking while attending appointments at the clinic with your surgeon.

**Voluntary Participation:**
Your participation in this study is voluntary. You may refuse to participate, refuse to answer any questions or withdraw from the study at any time with no effect on your future care. Should you choose to withdraw from this study, we will keep all data obtained up to the point that you chose to withdraw.

Participation in this study does not prevent you from participating in any other research studies at the present time or future. If you are participating in another research study, we ask that you please inform of us of your participation. You do not waive any legal rights by signing the consent form.

**Request for Study Results:**
Should you decide to participate and want to receive a copy of the study results, please provide your contact information on a separate piece of paper. Once the study has been published, a copy will be mailed to you. Please note that the results of this study are not expected for at least 5 years. Should your mailing information change, please let us know.

**Confidentiality:**
All information will be kept confidential to the best of our ability. The company that takes care of the research database is EmPower Health Research. Your identifying information (name, mailing address, phone number, email address, date of birth) is being collected as part of your participation in this study. Your data is protected by a username and password. It travels in a scrambled format to a server (storage computer) that is located in Montreal, Quebec, Canada. The company that houses the server is a professional company (Netelligent) with extremely high standards of physical and virtual security. We want to let you know however, that even with this high level of security, there is always a remote chance that your information could be accessed or "hacked" by someone who is not supposed to have your information. The chance that this information will be accidentally released is small. In any publication, presentation or report, your name will not be used and any information that discloses your identity will not be released or published.

Study data will be kept for seven years. Representatives of The University of Western Ontario Health Sciences Research Ethics Board may contact you or require access to your study-related records to monitor the conduct of the research.

**Questions:**

If you have questions about the conduct of the study or your rights as a research participant, you may contact Dr. David Hill, Scientific Director, Lawson Health Research Institute (519) 667-6649.

If you have questions or concerns about your surgery or physiotherapy, please contact your orthopaedic surgeon or physiotherapist. If you have any questions about this research, please contact Christopher Hewison at [redacted] or your orthopaedic surgeon.

This letter is yours to keep.

Sincerely,

Dr. Alan Getgood, MD
Dr. Dianne Bryant, PhD
Christopher Hewison, MSc (can.)
Nicole Kaniki, PhD (can.)
Alliya Remtulla, PhD (can.)
Chantel Arce, MSc (can.)
Michal Daniluk, MSc (can.)

FOWLER KENNEDY
SPORT MEDICINE CLINIC

**CONSENT FORM**

**Title of Research:**

Multicenter Randomized Clinical Trial comparing Anterior Cruciate Ligament Reconstruction With and Without Lateral Extra-articular Tenodesis in Individuals Who Are At High Risk of Graft Failure.

I have read the letter of information, have had the nature of the study explained to me, and I agree to participate in the study. All questions have been answered to my satisfaction. I will receive a copy of the Letter of Information and this signed consent form.

| ____________________ | ____________________ | ____________ |
|---|---|---|
| Printed Name of the Participant | Signature of the Participant | Date |

| ____________________ | ____________________ | ____________ |
|---|---|---|
| Printed Name of the Parent or Legally Authorized Representative (if required) | Signature of the Parent or Legally Authorized Representative (if required) | Date |

| ____________________ | ____________________ | ____________ |
|---|---|---|
| Printed Name of the Person Responsible for Obtaining Informed Consent | Signature of the Person Person Responsible for Obtaining Informed Consent | Date |

☐ I would like to receive a copy of the results of this study.
Please mail to:

_______________________________________

_______________________________________

_______________________________________

# Appendix D: Fowler Kennedy Physiotherapy Protocol Following ACL Reconstruction

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## PHYSIOTHERAPY FOLLOWING ACL RECONSTRUCTION PROTOCOL

Rehabilitation following Anterior Cruciate Ligament Reconstruction (ACLR) is an essential part of a full recovery. This protocol is intended to provide the user with instruction, direction, rehabilitative guidelines and functional goals. The physiotherapist must exercise their best professional judgment to determine how to integrate this protocol into an appropriate treatment plan. Some exercises may be adapted depending on the equipment availability at each facility. As an individual's progress is variable and each will possess various pre-operative deficiencies, this protocol must be individualized for optimal return to activity. There may be slight variations in this protocol if there are limitations imposed from additional associated injuries such as meniscal tears, articular cartilage trauma, bone bruising or other ligamentous injuries.

This rehabilitation protocol spans over a 6 month period and is divided into 7 timelines. Each timeline has goals and exercise suggestions for several domains: range of motion and flexibility, strength and endurance, proprioception, gait, and cardiovascular fitness. Criteria for progression within each timeline are based on the attainment of specific goals and on their Lower Extremity Functional Scale (LEFS) score. The focus in early rehabilitation is on regaining ROM, normalizing gait and activation of the quadriceps muscle. To ensure the best possible outcome for a safe return to the same level of activity prior to the injury, the client should be followed for the entire 6 months. The emphasis of rehabilitation should be focused at the 4-6 month mark. In these later stages, crucial skills such as plyometric training, agility drills, instructions on take-off and landing mechanics, patterning drills, and functional testing suggestions are given to determine the client's readiness for return to sport/activity.

***LOWER EXTREMITY FUNCTIONAL SCALE (LEFS)***

The LEFS is a self report questionnaire used to evaluate the functional status of an individual with a lower extremity musculoskeletal dysfunction. It is easy to administer and easy to score in the clinical and research environment. The LEFS consists of 20 items, each scored on a 5-point scale (0 to 4). Item scores are summed and total LEFS scores vary from 0 to 80, with higher values representing better functional status. The LEFS is a reliable and valid tool for assessing change in functional status. True clinically important change has occurred if the score changes 9 or more scale points from a previous score[51]. In each corresponding timeline of the protocol the ranges of the LEFS scores are presented. These scores were derived from data on 55 ACLR patients between the ages of 18-65 years of age from our facility. The LEFS scores provided should not be used in isolation as they are intended to be an adjunct to the protocol, the functional testing guidelines and to sound clinical reasoning.

***PRE-OPERATIVE REHABILITATION***

Rehabilitation should commence prior to surgery. After an ACL injury, deficits occur in strength[39], proprioception[40,56], muscle timing[55] and gait patterns[13]. In fact, strength and proprioceptive alterations occur in both the injured and uninjured limb[10,21,52,55]. The primary impairment with an ACL deficient knee is instability. This is manifested by episodes of 'giving way', which can lead to further joint damage and ultimately, long term degenerative changes[19]. Research has demonstrated that physiotherapy provided pre-operatively is effective in increasing strength and balance which may limit the number the episodes of 'giving way' and decrease the incidence of re-injury in the ACL deficient knee[18,26]. The main goals of a 'pre-habilitative' program prior to surgery include: full range of motion equal to the opposite knee, minimal joint swelling, adequate strength and neuromuscular control, and a positive state of mind[45]. All of these factors facilitate optimal post-operative recovery. It is important to maintain the highest level of strength and function possible in the unaffected leg as it will be used for comparison to assess the progress of the reconstructed knee, in the later stages of rehabilitation[22,23].

***RANGE OF MOTION & FLEXIBILITY*** [1,47,48]

After ACLR it is important to restore and maintain full range of motion (ROM) in the knee. Quadriceps re-training has been found to improve ROM in the early stages[44]. Attaining *full knee extension* as early as possible is *not* deleterious to the graft or to joint stability[43] and may prevent patellofemoral pain and compensatory gait pathologies. A stretching program is incorporated to maintain lower extremity flexibility. Research recommends that a 30 second stretch is sufficient to increase ROM in most healthy people. It is likely that longer periods of time, or more repetitions, are required for those individuals with injuries or with larger muscles. Body mass has been shown to be positively correlated with muscle stiffness (i.e., the bigger the muscle, the more stiffness/tension there exists)[34]. Therefore, for larger muscle groups in the lower extremity, it is suggested to increase in the number of repetitions (ie. 3-5 times) for optimal flexibility.

***Gait Retraining***

Altered gait kinematics from quadriceps dysfunction is typical during the first stages post ACL reconstruction. Typical adaptations include reduced cadence, stride length, altered swing and stance phase knee ROM, and decreased knee extensor torque with hip and/or ankle extensor adaptations[11,13,15,30]. Early weight bearing is advocated post ACLR in an attempt to restore gait kinematics in a timely fashion, facilitate vastus medialis function and decrease the incidence of anterior knee pain[53].

Treadmill training in the middle stages of rehabilitation can further assist in normalizing lower extremity ROM across all joints, especially with incline or backwards walking. Backwards treadmill walking has been shown in the literature to increase ROM and increase functional quadriceps strength, while minimizing patellofemoral stress. It is also beneficial for specific return-to-sport preparation requiring a re-training of backwards locomotion[49].

***Muscular Strength & Endurance Training***

Muscle analyses of the quadriceps post ACL injury have shown: i) similar degrees of atrophy in both type I (oxidative/endurance) and II (glycolytic/fast-twitch) muscle fibres, and ii) physiological metabolic shifts in muscle fibres from gylcolytic into oxidative compositions [35,50]. This means that ACL rehabilitation must include variable training parameters, which range from an endurance program of low load/high repetitions to a strength oriented phase of high load/low repetitions to focus on these deficits.

Depending on the graft type used for ACLR (patellar tendon vs. semitendonosis/gracilis), specific strength deficits have been found. With the patellar tendon graft, there are low velocity concentric extensor deficits specific to 60-95°; with the hamstring graft, there are high velocity, eccentric flexor deficits specific to 60-95°[23]. Strengthening exercises need to be velocity, ROM and contraction specific to address these deficits.

***Open (OKC) and Closed (CKC) Kinetic Chain Exercises***

OKC exercises have previously been contraindicated in ACLR patients for 6 months up to a year post-operatively, although the concern about the safety of OKC training in the early period after ACLR may not be well founded. It was originally thought that OKC exercises increased anterior tibial translation, with the possibility of increasing strain on the new graft. However, research has demonstrated that there are minimal strain differences between OKC leg extension and CKC activities such as squatting[4,5]. With the addition of OKC training, subjects have shown increased quadriceps torque increases without significant increases in laxity[25,37]. Researchers are now advocating the addition OKC exercises, ***at the appropriate time and within a restricted range,*** to complement the classic CKC rehabilitative program[25,37,38].

***Quality vs. Compensation***

Physiotherapists often feel compelled to progress patients by giving them new exercises each time they are in for therapy. It cannot be stressed enough that it is ***not*** beneficial to give patients exercises they are not neuromuscularly ready for. It is very important to observe the *quality* of the exercises that are being performed, specifically with CKC exercises. Weaknesses in specific muscle groups lead to compensations, which produce faulty movement patterns. These faulty patterns are then integrated into unconscious motor programs, which perpetuate the original weakness. Specifically, the research has indicated that knee extensor moment deficits are compensated for by hip and/or ankle extensor moments[11,15]. If these are allowed to occur and are not corrected, any joint or structure along the kinetic chain may be exposed to injury.

For example: A squat[16] or lunge must be performed with the trunk perpendicular to the ground (to avoid excessive hip flexion), the iliac crests must be level (to avoid Trendelenburg/hip hiking), and the knee must be over the foot with the tibia perpendicular to the floor (to avoid excessive dorsiflexion). It is better to decrease the range of movement (half squat vs. full squat) than to do the exercise at a level that is too difficult to perform correctly without compensation.

***Precautions with Hamstring Grafts***

The typical donor graft for ACLR at this facility is the hamstring (semitendinosis / gracilis). *Careful measures must be taken to avoid overstressing the donor area while it heals.* Although, isolated hamstring strengthening is initiated around the six-week mark in this group, it is important for the therapist to be aware of the natural stages of healing. There may be too much stress too early if the patient reports pain at the donor site during or after specific exercises.

***NEUROMUSCULAR & PROPRIOCEPTIVE RETRAINING***

Ideally proprioception should be initiated immediately after injury (prior to surgery), as it is known that proprioceptive input and neuromuscular control are altered after ACL injury[10,55]. By challenging the proprioceptive system though specific exercises, other knee joint mechanoreceptors are activated that produce compensatory muscle activation patterns in the neuromuscular system that may assist with joint stability[9].

Post-operatively, proprioceptive training should commence early in the rehabilitation process in order to begin neuromuscular integration and should continue as proprioceptive deficits have been found beyond 1 year post ACLR[11,15,21,32]. Proprioceptive exercises have been shown to enhance strength gains in the quadriceps and hamstring muscles post ACLR[31,57]. In the later stages of rehabilitation, anticipated and unanticipated perturbation training is effective in improving dynamic stability of the knee[8,18]. A dynamically stable joint is the result of an optimally functioning proprioceptive and neuromuscular system and functional outcome has been proven to be highly correlated with balance in the reconstructed ACL[46].

***RETURN TO SPORT***

Gradual return to sport is initiated at the 6-9 month mark *only* if the individual's knee does *not* present with pain or effusion, during or after functional sport specific training drills. LEFS scores should be 76 points or greater at this point in rehabilitation. The individual must also be able to demonstrate the appropriate strength and endurance needed for their specific sport. This recommendation is based on the evidence that knee cartilage and subchondral bone are damaged during the initial ACL trauma and may need additional time to recover in order to minimize the predisposition for future joint arthrosis[17,54,58].

A further consideration when returning the patient to sport is that a cautionary approach should be taken with the use of the uninjured limb as a comparison for a rehabilitation endpoint. It has been demonstrated in the literature that a significant detraining effect occurs in the quadriceps and hamstring muscles in both injured and uninjured extremities[22].

***BRACING***

Bracing should be discussed with the physiotherapist and surgeon prior to return to sport or strenuous activities post ACLR. The decision will be dependent on a number of factors including: type of sport, position, activity level and complexity of the initial injury. Some surgeons may recommend a rigid, functional knee brace or a neoprene sleeve. Research has demonstrated that a rigid knee brace does not provide superior outcomes when compared with a neoprene sleeve after ACLR[6]. Bracing has not been proven to prevent re-injury or improve clinical outcomes after ACLR[33]. However, there is evidence that any type of knee bracing (rigid /soft) improves proprioception measures[7,27].

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**0-2 WEEKS**

LEFS range: 14-24

***GOALS***

- Patient education re: weight-bearing status; changes to rehab guidelines with any concurrent pathologies (i.e. PF pain, MCL injury, meniscal repair vs debridement, etc.)
- Decrease pain and swelling
- Increase range of motion & restore full extension*
- Maintain flexibility of hamstrings, calves
- Quadriceps activation[44]
- Proprioceptive/balance re-education[46]
- Maintain cardiovascular fitness

***EXERCISE SUGGESTIONS***

*ROM & Flexibility*

> **Remember - It is important to restore and maintain range of motion early, especially full extension. This is not detrimental to the graft or its stability [43].*

- Heel slides (+/– slider board)
- Supine with legs up wall – heels slides with gravity assisted
- Bike pendulums: high seat ½ circles forward/backward → full circles – lower seat
- Sitting passive leg extension with roll under heel OR prone leg hangs off end of bed/plinth
- Seated calf stretch with towel - knee bent (soleus), knee straight (gastrocnemius)
- Seated hamstring stretch (back straight)

*Muscle Strength & Endurance*

*Quadriceps/Hamstrings:*

- Quadriceps and hamstring co-contraction[2,41]
- Quadriceps isometrics[44] in standing/sitting/lying +/– muscle stimulation or biofeedback
- Sit to stand – progress by gradually decreasing height of seat
- Static lunge forward/side
- Mini wall squat (30°)
- Shuttle™: (one bungee cord) – 2 leg squat (¼ - ½ range) and 2 leg calf raises

*Hip/Gluteals:*

- Side lying abduction/adduction
- Gluteal squeezes supine or standing
- Prone hip extension
- Standing hip flexion/extension, abduction/adduction

*Calves:*

- Ankle pumping +/– with leg elevation
- Standing calf raises with/without support

### Proprioception

*With balance drills on unstable surfaces, be aware of and correct poor balance responses such as hip hiking with INV/EVER and trunk extension with DF/PF.*

- Single leg stance 30-60 seconds
- Wobble boards with support (table, bars, poles) through full ROM: side-to-side, forward/backward

### Gait

*If patient has an antalgic gait pattern with use of 1 crutch, keep patient on 2 crutches until they can exhibit normal gait with 1 crutch.*

- Weight shifting: side-to-side and forward/backward[28]
- Progress from 2 crutches to 1, always maintaining normal walking pattern

**Modalities**

- Ice 15-25 minutes[24]
- Interferential current therapy (pain relief)
- Muscle Stimulation[49]

## 3-6 WEEKS

LEFS range: 32-50

GOALS

- Achieve near or full ROM in knee flexion and extension
- Continue flexibility exercises of other joints
- Continue strengthening exercises with control: hip, hamstrings, quadriceps, calves
- Strengthen non injured leg (documented strength losses in unaffected limb)[22]
- Progress proprioception
- Normal WB gait
- Maintain cardiovascular fitness

***EXERCISE SUGGESTIONS***

*ROM & Flexibility*

- Continue as needed with slider board
- Continue on the bike full with circles forward/backward - begin to lower seat
- Prone assisted knee flexion (belt, opposite leg)
- Progress to standing stretches for gastrocnemius (knee straight) and soleus (knee bent), ensure back foot is straight
- Progress to a standing hamstring stretch (keep back straight)
- Assisted quadriceps stretch in prone or in standing
- Patellar and/or tibial-femoral joint mobilizations if needed to achieve terminal ROM (no ACL strain with passive movement)[3]

*Muscle Strength & Endurance*

*Quadriceps:*

- Progress on Shuttle™ from 2-1 leg squats/calf raises, increase range of motion and resistance as tolerated
- Sit-to-stand with muscle stimulation[49]
- Leg press machine: low weight 2 legs (½ – ¾ range)

- Wall squats with feet 12" from wall (45°-60°)
- Forward and lateral step-ups 2-4" (push body weight up through weight bearing heel slow and with control, also watch for hip hiking or excessive ankle dorsiflexion)[4]

*Hamstrings/Gluteals:*
- Prone assisted hamstrings (with belt, opposite leg)
- Hip strengthening with pulleys or ankle weights - all directions (do not allow a lot of trunk swaying)
- Supine on floor legs on Swiss ball: isometric hamstrings/gluteals - progress to bridging (if pain free at donor site)

*Calves:*
- Standing calf raises 2-1 foot

**Proprioception**

| |
|---|
| *Progression of balance retraining should be from:* |
| *looking forward → looking away, eyes open → eyes closed, on a stable base → on an unstable base* |

- Continue with full ROM on wobble boards with decreased support - progress to maintaining balance on board
- Standing 747 eyes open/closed – progress to mini trampoline
- Dynadisc™ or BOSU™ (round) 2 leg balance → weight shift forward/backward, side-to-side, eyes open/closed → progress to mini squats (0-30°)
- Standing on ½ foam roller: balance → rocking forward/backward

**Gait**

| |
|---|
| **Full knee extension is needed for normal gait.* |

- "Cup walking"[14]: forced exaggeration of knee and hip flexion during the swing phase of gait rather than a rigid knee with a compensatory hip hike (may use plastic cups/mini pylons/foam rollers to walk over to accentuate hip/knee flexion)
- Progress from a single crutch to full weight bearing. Ensure NO antalgic gait pattern

*Cardiovascular Fitness*
- Bike with increasing time parameters
- May start elliptical trainer and progress to Stairmaster™[36] if adequate strength has been achieved (must have no hip hiking when pressing down on step)

**6-9 WEEKS**

LEFS range: 45-59

GOALS
- Full and pain free knee range of motion
- Functional quadriceps strength
- Initiate isokinetic quadriceps strengthening in a **specific & limited** range[37]
  **<u>only if</u>: ROM is full, no swelling, adequate muscle control, and no meniscal or patellofemoral pathology
- Address documented quadriceps strength deficits (high and low velocity, concentric and eccentric, 0-95°)[23]

- Continue strengthening lower extremity muscle groups, specifically through full range hamstrings/quadriceps (without pain at donor site)
- Advance proprioception exercises
- Increase cardiovascular fitness

***EXERCISE SUGGESTIONS***

*ROM & Flexibility*

- Mobilizations if needed to achieve end ranges

*Muscle Strength & Endurance*

*Quadriceps:*

- Terminal extension with tubing – forward and backward facing
- Shuttle™: full and inner range squats, 2 → 1 leg, increasing resistance
- Walking in Bungee™ cord forward/backward/side step with slow control on return
- Lunging in Bungee™ – forward/backward/diagonal
- Step-ups 6-8"step forward/lateral (vertical trunk, watch for hip hiking or excessive ankle dorsiflexion)
- Eccentric lateral step down on 2 → 4 → 6" step with control (watch for hip hiking or excessive ankle dorsiflexion)[15]
- Static Lunge (¼ - ½ range) → progress to dynamic lunge step (¼ - ½ range) with proper trunk and leg alignment
- Full wall squats to 90°
- Initiate isokinetic program if patient is appropriate and equipment is available
- (see reference for timelines and ROM restrictions)[37]**

*Hamstrings/Gluteals:*

- Continue hip strengthening with increased weights/tubing resistance
- Supine on floor legs on swiss ball: bridging plus knee flexion (heels to buttocks)
- Prone active hamstring curls – progress with 1-2 lb weights
- Standing hamstrings curls – when able to attain 90° ROM against gravity add 1-2 lb weights
- Sitting hamstring curls with light tubing/pulley system for resistance
- Fitter™: hip abduction and extension (poles for support)
- Shuttle™ standing kick backs (hip/knee extension)
- Tubing kickback (mule kicks)

*Calves:*

- Shuttle™ heel drops 2 → 1 leg
- Mini trampoline: weight shift heel drops/bouncing

**Proprioception**

- Continue on wobble boards and begin to add basic upper body skills (i.e. throwing)
- Mini trampoline: single leg stance, +/– Bodyblade™ above/below head
- BOSU™ marching: progress with high knees
- Progress Dynadisc™ or BOSU™ 1 leg balance with/without support
- Dynadisc™ or BOSU™ squats (60-90°)
- Dynadisc™ or BOSU™ stand on 2 legs, with throwing to Rebounder™

**Hydrotherapy / Pool**

- Knee ROM

- Walking forward/backward, static lunge, lunge walking, squats, side shuffles, step up/down, calf raises (2-1 foot)
- Hip extension/flexion, adduction/abduction
- Deep water: stride walking, cycling, flutter kick

*Cardiovascular Fitness*

- Bike, increasing time <u>or</u> resistance
- Stairmaster™: forward/backward – progress to no hand support
- Swim - Flutter kick only
- Pool jogging – deep water jogging
- Treadmill – walking, increase speed +/– visual (mirror) or auditory (metronome) feedback[12,20]

## 9-12 WEEKS

<u>LEFS range: 55-66</u>

***GOALS***

- Continue flexibility exercises
- Quadriceps strength progression
- Address documented hamstring strength deficits (high speed, eccentric 95-60°)[23]
- Continue lower chain concentric/eccentric strengthening of quadriceps & hamstrings, both inner range (60–95°) & full range
- Proprioceptive progression
- Sport specific cardiovascular fitness

***EXERCISE SUGGESTIONS***

*Muscle Strength & Endurance*

*<u>Quadriceps</u>:*

- Progress resistance of Shuttle™: full ROM and inner range (60-95°), working on strength & endurance, 2 → 1 leg
- Static Lunge (full range) → dynamic lunge → lunge walking all with proper trunk and leg alignment
- Backward step up 4-6-8" step
- Clock face lunges with Bungee™ using mini pylon markers
- Quick walk forward/backward with Bungee™
- Quick side stepping with Bungee™
- Quick lunge forward with control (upright trunk, no forward thrust, no hip hiking)
- Eccentric Bungee™
- Eccentric step down with control on 6 → 8" step
- Shuttle™ jumping (low resistance) 2 legs →alternate legs (jogging) →single leg
- Shuttle™ ski hops (side-to-side)
- Continue / progress isokinetic program if patient is appropriate and equipment is available (see reference for timelines and ROM restrictions)[37]**

*<u>Hamstrings/Gluteals</u>:*

- Prone/standing pulley knee flexion
- Chair walking
- Prone eccentric hamstrings with pulleys/tubing, alternating inner range and full range
- Hydrafitness™ (hamstrings & quadriceps): 90-30°, resistance 1-3

- Continue hip strengthening with increased weights/tubing resistance
- Sitting and standing hamstring curls – Bungee™/pulleys/ weights sitting and standing positions - address full range concentrically and inner range from 95-60° eccentrically and high velocity (if pain free & without difficulty)
- Supine eccentric hamstrings with knee in extension

*Calves:*
- Eccentric heel drops

*Proprioception*
- On boards/Dynadisc™/BOSU™/foam roller/mini trampoline: catch and throw (2 hands/1hand) at varying angles and directions with partner or using rebounder
- Dynadisc™ or BOSU™ throwing on rebounder feet side-to-side, forward/backward, 2-1 foot
- Perturbation drills[8,42] with tubing on boards/ Dynadisc™/BOSU™ /foam roller/mini trampoline
- Single leg stance on Dynadisc™ or BOSU™ with unaffected leg performing kicking drills +/– tubing/pulleys
- Single leg stance on Dynadisc™ or BOSU™ performing kicking drills +/– tubing/pulleys
- Single leg stance on Dynadisc™ or BOSU™ performing higher end upper body skills

**Hydrotherapy / Pool**
- Increase time, speed, repetitions of exercises
- Pool running

*Cardiovascular Fitness*
- Bike: increased resistance and time parameters
- Fitter™: slalom skiing without ski pole support
- Treadmill walk +/– incline[29] → quick walk

## 12-16 WEEKS

LEFS range: 55-66

***GOALS***
- Continue with flexibility exercises for the lower chain
- Continue strengthening of the lower chain
- Sport specific quadriceps & hamstrings strengthening
- Sport specific proprioception training
- Sport specific cardiovascular fitness

***EXERCISE SUGGESTIONS***
**Muscle Strength & Endurance**
- Continue with concentric and eccentric strengthening of hamstrings and quadriceps, working through full & inner range
- Backward lunge – progress to backward lunge walking (with proper trunk and leg alignment)
- Bungee™ jogging - progress to running
- Split squat jumps – progress to BOSU
- Single leg drop landing 2" step

*Agility*

*Agility is the ability to move, and change direction and position of the body quickly and effectively with control.*

- Ladder drills – forward/backward, side-to-side (focus on footwork/speed/timing)
- 2 legged lateral and forward jumping
- Side step-overs (hurdle) – progress to side hop-overs
- Carioca patterning
- Tuck jumps
- Skipping
- Initiate 2 legged hop tests (hop for distance, 6-m timed hop, triple hop, crossover hop) prior to single leg hop tests in next stage - ensure patterning and landing is proficient prior to 1 leg progression

*Proprioception*

- Mini trampoline: 2 feet jump & land →jogging →1 leg hopping (1L/1R, 2L/2R, 3L/3R…)
- Continue progressing skill difficulty
- Single leg stance – tap down clock drill with mini pylons
- Dynadisc™ or BOSU™: 1 leg balance with upper body or opposite leg skill i.e. throwing, phantom kicking with Bungee™ resistance, hockey shot….

**Hydrotherapy / Pool**

- Progress to plyometrics: 2 leg hopping, forward/backward/side-to-side
- Split squat jumping

*Cardiovascular Fitness*

- Bike – standing with interval training
- Sport specific cardiovascular training: aerobic vs. anaerobic training
- Jogging – straight on flat ground, no cuts/no downhill
- Treadmill – jog → interval running→ running

**Note: Progression to running may only occur once a symmetric and proficient pattern has been attained to prevent abnormal tissue/joint loading in the lower extremity. Running should NOT be initiated if swelling, loss of motion or patello-femoral pain is present.*

**16-20 WEEKS**

LEFS range: 61-76

***GOALS***

- Sport specific quadriceps, hamstrings and lower chain strengthening progressing to plyometrics
- Proprioception training
- Sport specific cardiovascular fitness

***EXERCISE SUGGESTIONS***

*Muscle Strength & Endurance*

- Continue with lower extremity strengthening with specific emphasis on client–specific deficits
- 2 → 1 leg progression for all exercises

**Plyometrics and Agility**

*Plyometrics are exercises that enable a group of muscles to reach maximal strength in as short a time as possible. They help bridge the gap between speed and strength training. Adequate concentric & eccentric strength is essential before initiating plyometrics. If needed, start them in the pool in shallow water to decrease stress on the tibiofemoral and patellofemoral joints; otherwise initiate on land as tolerated.*

*Agility drills should commence by introducing proper footwork, timing and speed. Once the client is able to successfully and appropriately run in a straight line,without difficult, non-linear activities may be initiated, such as cutting and pivoting. These drills should commence by introducing large angles and low speeds (ie. large figure 8s) and progress to more advanced drills with sharper angles and increasing speeds*[20]

- Ladder drills – incorporate lateral movements/diagonals, adding single leg and crossover patterns
- Running/lunging/vertical jump/ run-plant-sidestep with Bungee™ - may incorporate upper/lower body skill – kicking, jumping, catching, pass & shoot
- Shuttle™ hopping 2 – alt – 1 (high resistance, increased speed)
- Shuttle™ Ski hops (high resistance, increased speed)
- Carioca ¾ jog
- Mini trampoline: 2 leg jump off – 2 leg land with progression to one leg land on/off balance pad/BOSU (watch for proper landing mechanics)
- Single leg forward and lateral hopping
- Hop tests: single hop, 6-m timed hop, triple hop, crossover hop
- Vertical jumps – single leg
- Box hop up /down
- Box jump down with sprint forward
- Box drop jump 2 legs with proper form may progress to drop jump with vertical hop for maximum height
- Single leg drop landing 4-6-8-10" step

*Proprioception*

- Continue progressions e.g. mini trampoline with upper skills
- Forward hop and lateral hop – maintain balance for 5 sec on landing
- Cutting drills with quick stop and maintain balance
- Bungee™ run plant/push off L&R

**Cardiovascular Fitness**

- Increase distance, duration or intensity with bike, Stairmaster™, treadmill, outdoor running/cycling depending on the demands of the particular sport
- Treadmill: running → sprinting: assess sprinting form - should have normal pain-free rhythmic stride (audible monitoring of foot contact)[20]
- Jogging and running on an uneven surface
- Jogging with turns 90/180/360°
- Jogging and cutting with 45° change of direction
- Acceleration and deceleration running, add on tight turns and hills as tolerated
- Cycling outdoors
- Swimming - no whipkick

## 20-24 WEEKS

LEFS range: 61-76

***GOALS***

- Adequate cardiovascular fitness, strength, power, agility neuromuscular control, symmetry and stability
- Continue with upper body strengthening
- Back to sport practice for upper skills (as able)
- Return to sport skills on own at practice with minimal risk of re-injury

***EXERCISE SUGGESTIONS***

*Plyometrics and Agility*

- Single leg drop jump 6" step
- Large Figure 8's
- Carioca running full speed
- Last minute decision drills
- 2 and 1 foot hopping with control
- Forward and lateral hop with control and comparable distance L&R
- Triple jump and landing with control and comparable distances L&R
- Single limb hop for distance (within 15% of uninvolved side)
- Single-limb crossover triple hop for distance (within 15% of uninvolved side)
- Single-limb timed hop over 6 m (within 15% of uninvolved side)
- Single limb vertical power hop (within 15% of uninvolved side)
- Single limb drop landing (within 15% of uninvolved side)
- Single limb drop-jump
- 10 second single limb maximum vertical hop (both sides)

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[redacted]

## Appendix E: Data Collection Form

PID: ___________________________ Date: ___________________________

Database ID: ___________________ Subject #: ______________________

Followup: ☐ 6 months ☐ 1 year ☐ 2 years

**DATA COLLECTION FORM**

Age: _______________ Height (cm): ________________

Sex: _______________ Mass (kg): ________________

**Affected Limb:** ☐ Left ☐ Right

**Anthropometric measures (cm)**

R. Foot Length: ____________ R. Foot Width: ___________ L. Foot Length: ____________ L. Foot Width: _________

R. Knee: _____________ R. Ankle: ___________ L. Knee: _____________ L. Ankle: __________

**Pain:** _____ /10 (Pre) **Medication:** _____________

_____ /10 (Post)

| | Trial Number | Complete | Tracked | Exported |
|---|---|---|---|---|
| Standing Static 3 seconds | 1 | | | |
| Standing Static 3 seconds | 2 | | | |
| Static Box | 3 | | | |
| EMG Tib Ant | 4 | | | |
| EMG Gastroc | 5 | | | |
| EMG Quad | 6 | | | |
| EMG Hamstring | 7 | | | |
| DVJ | 8 | | | |
| DVJ | 9 | | | |
| DVJ | 10 | | | |
| DVJ | 11 | | | |
| DVJ | 12 | | | |

**EMG Placement:**

| | |
|---|---|
| **1.** Rectus | **5.** Vastus Lateralis |
| **2.** Vastus Medialis | **6.** Lateral Hamstring |
| **3.** Medial Hamstring | **7.** Medial Gastroc |
| **4.** Lateral Gastroc | **8.** Tib Ant |

Patient Initials: _____
Version: March 30th, 2016

# Curriculum Vitae

**Name** **LINDSEY O'NEILL**

## Education

**Master of Science:**
Health and Rehabilitation Sciences
Thesis Based – Physical Therapy
Western University, London, ON, Canada.
September 2016 – August 2018

**Bachelor of Science:**
Honours Kinesiology
Management Studies Minor
University of Waterloo, Waterloo, ON, Canada.
September 2012 – April 2016

## Awards

**Western University** Western Graduate Research Scholarship – Rehabilitation Sciences ($3650.38) – 2016/17

**University of Waterloo** Applied Health Sciences Entrance Scholarship ($500) – 2012

## Research Experience

**Western University**
**Graduate Student**
2016 – 2018

STABILITY Study: A Multicentre Randomized Clinical Trial Comparing Anterior Cruciate Ligament Reconstruction With and Without Lateral Extra-Articular Tenodesis in Individuals at High Risk of Graft Failure.
Supervisors: Dr. Trevor Birmingham

## Related Work Experience

**Western University**
**Teaching Assistant**
2016 – 2017

HS 2300A/B: Systemic Approach to Functional Anatomy
Professor Jamie Melling

**Western University**
**Teaching Assistant**
2017 – 2018

HS 2300A/B: Systemic Approach to Functional Anatomy
Professor Gillian Corbo

**Presentations**

**Oral Presentation**
February 2016

ACL Prevention: Neuromuscular Training
*Seminar – University of Waterloo*

**2-minute Elevator Pitch**
November 2016

A Multicenter Randomized Clinical Trial Comparing Anterior Cruciate Ligament Reconstruction With and Without Lateral Extra-Articular Tenodesis in Individuals at High Risk of Graft Failure.
*Physical Therapy Seminar – Western University*

**Poster Presentation**
January 2017

Drop Vertical Jump Landing Mechanics Following Anterior Cruciate Ligament Reconstruction With and Without Lateral Extra – Articular Tenodesis
*Western University*
*Health &Rehabilitation Sciences Graduate Research Conference*

**Oral Presentation**
May 2017

Comparison of Drop Vertical Jump Landing Mechanics in Patients Undergoing Anterior Cruciate Ligament Reconstruction With and Without Lateral Extra-Articular Tenodesis
*Research Rounds – Western University*

**Oral Presentation**
*Co-author*
June 2017

Drop Vertical Jump Landing Mechanics Following Anterior Cruciate Ligament Reconstruction With and Without Lateral Extra-Articular Tenodesis – 6 Month Results from the ISAKOS Sponsored Stability Study
*Presented by: Dr. Alan Getgood*
*2017 ISAKOS Congress – Shanghai, China*

**Poster Presentation**
*Co-author*
July 2017

A Randomized Trial Comparing Drop Vertical Jump Landing Mechanics in Patients Undergoing Anterior Cruciate Ligament Reconstruction With and Without Lateral Extra-Articular Tenodesis
*Presented by: Michal Daniluk*
*2017 AOSSM Annual Meeting – Toronto, Canada*

**Oral Presentation**
*Co-author*
July 2017

Lateral Extra-articular Tenodesis Does Not Influence Knee Abduction Moment During Drop Vertical Jump Following ACL Reconstruction
*Presented by: Dr. Alan Getgood*
*2017 AOSSM Annual Meeting – Toronto, Canada*